UTILIZATION OF INDUSTRIAL BY-PRODUCTS FOR DEVELOPMENT OF CONTROLLED LOW STRENGTH MATERIALS (CLSM)

A Thesis

Submitted in fulfilment of the requirements for the award of the degree of

DOCTOR OF PHILOSOPHY

by

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CERTIFICATE

Certified that the thesis "**Utilization of industrial by-products for development of controlled low strength materials (CLSM)**" which is submitted by Mr. **Jaideep Aggarwal**, in fulfilment of the requirement for the award of the degree of **Doctor of Philosophy** in the Department of Civil Engineering, Thapar Institute of Engineering & Technology, Patiala, is a record of the candidate's own independent and original research work carried out by him under our supervision and guidance. The matter embodied in this thesis has not been submitted in part or full to any other University or Institute for the award of any degree.

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DECLARATION

I hereby declare that the work presented in the thesis entitled "**Utilization of industrial by-products for development of controlled low strength materials (CLSM)**" in the fulfilment of the requirement for the award of the Degree of **Doctor of Philosophy** in the Department of Civil Engineering, Thapar Institute of Engineering & Technology, Patiala, is an authentic record of my own work during the period July 2015 to June 2024, under the supervision of **Dr. Shweta Goyal**, Professor, Department of Civil Engineering, Thapar Institute of Engineering & Technology, Patiala and **Dr. Maneek Kumar**, Professor and Dean, School of Engineering & Technology, BML Munjal University, Gurugram. The material embodied in this thesis has not been submitted in parts or full in any other university or institute for the award of any degree in India or Abroad.

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ABSTRACT

A controlled low strength material (CLSM) is a self-compacting flowable material using a small quantity of binder, fine aggregate and water, and are primarily employed as backfill. The specified upper limit of 28-day compressive strength for CLSM is 8.30 MPa and for future excavatability as 2.10 MPa. The low strength requirements of CLSMs make them suitable to allow utilization of low-quality industrial by-products as constituents as substitutes for conventional materials. The present study envisaged the development of sustainable CLSM suitable for practical applications, by utilization of industrial and agro by-products cement kiln dust (CKD), spent foundry sand (SFS) and unprocessed rice husk ash (RHA). For the above purpose, engineering properties of the CLSM mixes in the fresh and hardened states were evaluated. In order to ensure environmental safety for using the CLSM as backfill, these mixes were also examined in terms of their leachate toxicity.

The study has been divided into three groups based on the by-products used. In Group-1, spent foundry sand completely substituted the conventional fine aggregates, while cement kiln dust replaced cement at 0%, 25%, 50%, 75% and 100% levels to form five mixes. The binder to aggregate ratio was 1:10 and water content was worked out for the flowability of around 250 mm. Addition of cement kiln dust increased flow, delayed setting time and reduced the compressive strength. The findings also indicated that spent foundry sand with 100% cement kiln dust could be successfully utilized to prepare excavatable, eco-friendly and sustainable CLSM with bearing resistance equivalent to well compacted sands, suitable for general purpose backfill. The mix with 75% cement kiln dust proved most suited from most of the aspects of a practical CLSM.

In Group-2, rice husk ash was used as fine aggregate and five CLSM mixes with cement kiln dust (CKD) replacing cement like in Group-1 were studied. The binder to aggregate ratio was 1:3 and water content was worked out for the flowability of 200-250 mm. The addition of cement kiln dust increased flowability, bleeding, setting time and reduced compressive strength. The mixes with 75-100 % CKD could not attain the desired stiffness level of final setting time for a penetration resistance of 2.76 MPa. With respect to unconfined compressive strength, all the Group-2 mixes were manually excavatable and suited general backfill applications like voids, abandoned underground structures. However, the CLSM mix with 50 % CKD was best suited with respect to practical requirements of reasonable setting time alongside strength.

In Group-3, proposed CLSM mixes comprised of spent foundry sand and unprocessed rice husk ash in 50:50 ratio (w/w) as fine aggregate. Five mixes with CKD and cement similar to Group-1 and Group-2 were formulated. The binder to aggregate ratio was 1:3 and a target flowability of around 200 mm was achieved. The addition of CKD resulted in a marginally higher water demand for 0-75% CKD followed by a lower demand at 100 % CKD. Further addition of CKD also delayed setting and reduced the compressive strength. The results presented the possibility of development of an environmentally safe, excavatable CLSM entirely by use of spent foundry sand, rice husk ash and cement kiln dust. The mix with 75% CKD met almost all desirable practical requirements of CLSM.

Heavy metal concentrations in the leachate of prepared CLSM mixes comprising all the proposed by-products were also within the regulatory levels. Therefore, use of the above by-products in the development of CLSMs was environmentally safe from the leachate toxicity aspect.

Ecological analysis of all the group CLSM mixes also showed diminished embodied energy and embodied carbon by use of by-products. Therefore, it was ecological to incorporate by-products in CLSM. For maximum benefit, the proposed application near the by-product's source shall minimize transportation energy in addition to above ecological advantage.

CLSM made by using by-products CKD, SFS and RHA can prove to be an innovative sustainable construction material facilitating valorization of agro-based and industrial by-products along with providing an effective infrastructural solution for their large-scale disposal.

LIST OF PUBLICATIONS

The following publications in peer reviewed journals are the outcome of the present research work:

1. **Aggarwal, J.**, Goyal, S., & Kumar, M. (2023). Sustainable utilization of industrial by-products spent foundry sand and cement kiln dust in controlled low strength materials (CLSM). ***Construction and Building Materials***, *404*, 133315. **Impact factor: 7.4**
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Chapter 1

INTRODUCTION

1.1 GENERAL

An expanding construction industry is the major consumer of non-renewable natural resources and energy. It is causing increasing green-house gas (GHG) emissions and raised earth temperature due to the calcination reaction for cement clinker and combustion of fossil fuel (Abdel-Gawwad et al., 2020; de Azevedo Basto et al., 2019). Also, the resulting increased wastes generation leads to rising operational cost and landfill space problems (Alexander et al., 2024). Continued exploitation of non-renewable natural resource i.e., limestone for cement production and river sand to cater to aggregate requirements in construction activities are causing an ecological imbalance (Dixit, 2020). A ton of cement requires 1.5 tons of raw materials i.e., limestone and sand (Rashad, 2014) and generate 0.94 tons of carbon dioxide (Pacheco-Torgal et al., 2012) owing to burning of fuel, the calcination process and clinker grinding etc. Pertinently, the cement industry contributes around 5-7% to the global CO_2 emissions (Bhagat et al., 2021; Chen et al., 2010; Geng et al., 2019), while the overall concrete industry consuming 2-3% of the global energy, contributes 8-9 % of GHG (Thomas et al., 2021). Also, excessive river mining catering to the global requirement of around 50 billion tons of aggregates (Bhardwaj et al., 2022; UNEP, 2019) causes deterioration of river beds triggering natural calamities in the form of floods, landslides etc. (Revilla-Cuesta et al., 2022; Santhosh et al., 2021). The need of the hour is to reduce the consumption of cement and river sand by replacing these by environment friendly options like by-products from industry (Bassani et al., 2017; Bhardwaj et al., 2022; Najim et al., 2016; Santhosh et al., 2021).

1.2 INDUSTRIAL BY-PRODUCTS IN SUSTAINABLE DEVELOPMENT

Sustainable development caters to the present day requirements of the world while taking care of the future generation’s needs (Abubakar et al., 2012; Brundtland, 1987; El-Attar et al., 2017). This is achievable by some of the following measures; a conservative approach in using natural materials, minimally polluting the natural resources and reducing waste generation. Further, the sustainable materials are beneficial man-made resources based upon industrial by-products that would have adversely impacted the environment if left unattended (Jayanthi and Singh, 2016). Thus, recycling of wastes or by-products generated by various industries in the construction sector gains high importance keeping in view the sustainability, cost effectiveness and environmental advantages (Abdelfatah and Tabsh, 2011). According to this new vision, recycling of wastes/by-products to partially substitute cement is highly encouraged for limiting the environmental impact of cement industry and converting these wastes into useful products. Industrial by-products, being considered as substitutes for secondary binders and/or aggregates, may not be fulfilling the requirements of conventional concrete and bituminous mixes but may be gainfully incorporated in construction elements supposed to resist the low stress and attrition environment (Bassani et al., 2017).

Many by-products with pozzolanic characteristics such as fly ash, blast furnace slag, limestone, silica fume, rice husk ash (RHA), palm oil fuel ash, cement kiln dust (CKD), metakaolin as well as natural pozzolana etc. are reported to be used as a substitute for cement in concrete/mortar with the recommended substitution levels of around 5-30 % (Abdulredha et al., 2021; Ahmad et al., 2019; Hamada et al., 2023a, 2023b, 2021; Hussian, 2021; Korde et al., 2019; Pillai et al., 2020; Ramanathan et al., 2020; Singh et al., 2022; Wang et al., 2014). Generally other industrial by-products like quarry dust, stone processing dust, coal cinder, coal bottom ash (CBA), crushed waste glass, waste foundry sand and rubber aggregate etc. have been used either as the filler or replacement of the natural aggregates (Bhardwaj et al., 2022; Chaturvedy and Pandey, 2022; Gupta et al., 2019; Hamada et al., 2022a, 2022b; S. Kumar et al., 2022; Martins et al., 2019; Raman et al., 2011; Santhosh et al., 2021; Smarzewski and Barnat-Hunek, 2016). However, most of the studies have recommended generally up to 30 % replacement levels for the by-products in conventional construction products such as mortar and concrete for having desirable mechanical properties uncompromised. Therefore, it is required to explore other applications that utilize by-products in larger proportions so as to add to the existing avenues for adjusting the growing volumes of industrial by-products. In this context, three by-products that are available in abundance i.e., CKD from cement industry, spent foundry sand from metal casting industry and bio-mass based RHA from agriculture, are focused in the present study. The quantum of generation of the above-mentioned by-products and the hazards of disposing the same in landfills needed active consideration in order to find more methods for their safe disposal.

CKD is a fine-grained, solid, highly alkaline material extracted out of the exhaust gases from cement kilns by air pollution control devices (Stroup-Gardiner and Wattenberg-Komas, 2013). CKD generally has a chemical composition similar to cement, having major compounds alumina, silica, calcium oxides but with higher amount of sulphates and alkalis etc. (Lachemi et al., 2010). High free-lime, chloride and alkalis restrict CKD's reintroduction in the cement manufacturing process (Abdel-Gawwad et al., 2020; Pierce and Williams, 2012) and press for the need to find alternatives for large scale utilization of the same (Kaliyavaradhan et al., 2020). Gross CKD is generated at around 19% of the total cement product by wet kiln process and 23% by dry kiln process after recycling 40% in wet and 70% in dry process (United States Environmental Protection Agency (US EPA), 1993), a substantial quantum of CKD still required to be disposed of. With an annual global cement production of around 4.16 billion tons (“Cement - IEA,” n.d.; Mohamad et al., 2021), generation of a huge quantity of CKD is imminent. Further, about 80 % of the disposable CKD is required to be landfilled (Alharthi et al., 2021) that also poses issues like, degradation of the environment due to exposure to underground water, surface water and air along with landfill space constraints. CKD is considered a hazardous material due to its negative impact on the eyes, skin, and respiratory system in terms of Occupational Safety and Health Administration (OSHA), the hazard communication standard (Al-Bakri et al., 2022; Heidelberg Materials, 2023). CKD is also a potentially hazardous waste due to its caustic nature (Bobicki et al., 2012; Hanifa et al., 2023). Further, the toxicity examination of CKD on the case-to-case basis is recommended to be safe. The above issues justify the need for robust environment friendly methods for CKD’s disposal.

High quality size specific silica sand, used in foundries for preparation of moulds for ferrous and non-ferrous casting, is recycled and reused many times for casting and is ultimately disposed-of when it is no more reusable. The disposed-of silica sand is named as waste or spent or used foundry sand (SFS). Estimated generation of SFS is approximately one ton for every ton of metal casting (Gedik et al., 2018; David Trejo et al., 2004). Globally, about 109 million tons of metal castings (WFO, 2021) produce about 6-10% of the total weight of castings as spent foundry sand (Bhimani et al., 2012) annually and after nearly 30% recycling, the remainder is stored around foundries (Ahmad et al., 2022). Citing the possibility of leaching of elements like Al, Fe, Mn and phenols leading to contamination, the waste foundry sand is classified as a hazardous waste according to the minimum requirements for the handling, classification and disposal of hazardous waste as per South African standards (Iloh et al., 2019). Waste foundry sand is termed as hazardous material as per European regulations because of the presence of organic pollutants such as phenols and inorganic elements such as lead, chromium, cadmium, iron and zinc which are highly toxic and can contaminate the atmosphere or condense in the sand (Iqbal et al., 2020). Therefore, huge quantities of waste foundry sand need better avenues for disposal rather than being consigned to landfills.

Rice husk, which is around 28 % of the 500 million ton rice production globally (Abolhasani et al., 2022; Siddika et al., 2021; Statista, 2023; Thiedeitz et al., 2022) with very high calorific value (Della et al., 2002; Yu, 2014), is generally used as fuel in boilers in various industries. Each ton of rice husk after being burnt gives about 0.18-0.25 ton of ash known as RHA (Muthadhi et al., 2007; Siddika et al., 2021, 2018). RHA being light weight, its annual generation of around 30 million ton is likely to be voluminous. Also India, with an estimated 136 million ton rice production (Press Information Bureau, 2023) as the second largest rice producer in the world, is able to use only 1 % of the total RHA generation (Jittin et al., 2020; Yu, 2014). Most of it is generally dumped in the landfills (Siddika et al., 2021) or places nearby to the plants creating handling issues due to limited space (Ahsan and Hossain, 2018) as well as giving rise to pollution. Use of RHA in land filling is an environmentally hazardous way of disposing of the waste (Gidde and Jivani, 2007). Crystalline silica in RHA is classified as a human lung carcinogen and the inhalation of crystalline silica can cause silicosis, which is a severe or even fatal lung disease (OSHA, 2024; Yu, 2014). Thus, a huge quantity of unused RHA requires safe disposal solutions.

Various industrial by-products such as fly ash, iron slag, copper slag, rice husk ash, used foundry sand, bottom ash, quarry dust, cement kiln dust, incinerator ash, wood ash, recycled waste LCD glass, stainless steel reducing slag etc. have been considered in research for examining the possibility of utilizing these wastes as construction materials. Being a by-product, a sustainable material does not need any separate manufacturing process and therefore, their utilization for infrastructure development shall definitely be greatly advantageous (Jayanthi and Singh, 2016). One such apt option is using these by-products in the development of controlled low strength materials (CLSM) as a sustainable material.

1.3 CONTROLLED LOW STRENGTH MATERIALS (CLSM)

Backfilling is a major activity in any construction project. In general practice, use of soil as the fill material is associated with the problem of settlement. Any backfill needs high compaction to attain desired strength characteristics but the same is less successful in many situations like narrow trenches for pipe bedding where the compaction process is very difficult. There was need for new engineering solutions or alternative materials to substitute for soil to solve the above problems. This led to the idea of controlled low strength materials (CLSM). CLSM is a construction material that fulfils desirable requirement of a good backfill such as the required bearing strength, no or least settlement and excavatability. As per ACI 229R (1999), CLSM is defined as a self-compacting, highly flowable material primarily used as a backfill.

Conventionally CLSMs are composed of cementitious material, fine aggregate and water. Additives such as chemical admixtures, air-entraining agents, foaming agents, and accelerators etc. are also used for specific characteristics in CLSM. Coarse aggregate is generally not used in CLSM, however when used it is recommended to be equal to the fine aggregate content. The self-levelling property, lower setting time and lesser construction time of CLSMs offer many advantages like low labor cost, easier placement even in congested locations, the requirement of a lesser construction equipment as well as future excavatability (Du et al., 2002; Parhi et al., 2023) and therefore CLSMs are energy efficient also. CLSMs are also known by some other terms namely controlled density fill, unshrinkable fill, flowable fly ash, fly ash slurry, flowable mortar, flowable fill, soil-cement slurry, and plastic soil-cement, and also by commercial names such as S-Crete, K-Crete, and M-Crete (Parhi et al., 2023). CLSMs generally have many applications such as backfills, structural fills, insulating and isolating fills, pavement bases, conduit bedding, erosion control, void filling and bridge reclamation etc. (ACI 229R, 1999; Bassani et al., 2017). CLSM has been used in transportation infrastructure, like pipe-trench, abutment-backfill, retaining-wall and subgrade due to its advantages of easier making, placement and small settlement (Sheen et al., 2013; Wu and Tsai, 2009). Very different from conventional concrete, CLSM has an upper limit for unconfined compressive strength (UCCS) as 8.3 MPa and further it is considered excavatable when its UCCS is below 2.1 MPa (ACI 229R, 1999). The low strength of CLSM ensures easy future removability of the backfill in an event a buried element like the pipeline requires replacement or repair (Gemperline, 2011).

In view of no standard procedure being available for proportioning of CLSM constituents, past experience and trial and error are the only practices followed and further the characteristics and quantity of the mix materials are the main important parameters that control prime requirements i.e., high flow and controlled strength of CLSM (Ling et al., 2018a). The low strength and stiffness requirements of the CLSMs make them suitable for using alternative low-cost, energy saving materials like industrial by-products etc. in replacement of conventional non-renewable resources and binders namely aggregates and cement (Bassani et al., 2017; Parhi et al., 2023). Using by-products as construction materials also ensures reduced pollution, preservation of natural resources and saving of valuable landfill space that would be required to dispose-of the by-products in case they are not used/recycled, and this promotes sustainability along with revenue generation (Do and Kim, 2016; Razak et al., 2009). However, it is recommended that the characteristics of the prospective non-standard material be checked for acceptability in CLSM before use.

The historical background of CLSM reveals its application by U.S. Bureau of Reclamation, as early as in 1964 wherein bedding work under a 518 km long pipeline using CLSM was executed along the Canadian River Aqueduct project (ACI 229R, 1999; Parhi et al., 2023). Later flowable fly ash was developed as a substitute for compacted granular fill in 1970s by the Detroit Edison Company and Kuhlman Corporation utilizing fly ash (FA) and concrete batching technologies (Funston et al., 1984; Krell, 1989). In 1974, K-Krete Inc. developed a typical K-Krete mixture using cement, fly ash, filler material, and water (Larsen, 1990). Later in 1977, the rights of four patents from K-Crete regarding design, backfill technique, pipe bedding, and dike construction practices got assigned to the National Ready Mix Concrete Association (NRMCA) with the mandate for the rights not to be used in a proprietary way. Thereafter, producers and contactors of ready-mixed concrete have been using similar materials to K-Krete without any patent conflicts (D. Trejo et al., 2004; Wang, 2004). Still, there was a lack of any centralized agency for getting information which caused confusion and hesitation in the concerned community to adopt the new materials. ACI Committee 229 constituted in 1984 submitted a report titled “Controlled Low-Strength Materials (CLSM)” that was made public in 1994 and finally effective in 1999 (Ling et al., 2018a). The American Society for Testing and Materials (ASTM), in 1998, issued a book titled “The Design and Application of Controlled Low-Strength Materials (flowable fill)” containing CLSM production in the laboratory and the field (Howard, 1998; Ling et al., 2018a).

1.3.1 Advantages of CLSM

Ready availability, easy delivery and placement: A ready-mix concrete facility can easily prepare CLSM with suitable local materials meeting specific project requirements, deliver by ready mix trucks at site and place it at the desired location with appropriate equipment like chute, conveyer, pump etc. The self-levelling property of CLSM ensures no requirement for compaction and spreading which speeds up construction and reduce labour requirements.

Versatility: Depending upon the requirements CLSM mix designs can be easily altered for strength and flowability by varying constituents like water, cement or fly ash while adding admixtures for desired setting time and other parameters and foaming agents to get a lightweight, insulating fill.

Strength, durability and excavatability: CLSM typically have higher allowable bearing pressure compared to a compacted granular soil/fill, less permeability, more resistant to erosion. CLSM can be designed to a 28-day compressive strength as high as 8.30 MPa suitable for a permanent structural fill. Still, CLSM having strength of 0.35 to 0.70 MPa can be easily excavated with conventional equipment but also strong enough for most backfilling requirement.

Less inspection: The self-compacting nature of CLSM may not require much monitoring as compared to a normal soil backfill requiring continuous compaction checks on completion of each layer.

Quick traffic restoration: Quick placement and desired hardening facilitate traffic restoration with minimal downtime for repairs.

No settlement: The strength of CLSM allowing no settlement or rutting under loads is quite significant for an overlaid pavement patch since soil/granular fill without due consolidation tends to settle and cause cracks or dips in the road.

Excavation cost-effective: Narrower trenches are possible due to flowability and the no compaction requirement of CLSM, since wide trenches would be needed for operating compaction equipment for a soil backfill.

Worker safety: Exposure of workers to possible cave-ins is reduced due to the possibility of remote placing of CLSM without entering a deep/narrow trench.

All-weather construction: CLSM's ability to displace any standing water owing to rain or melting snow in trenches ensures continued construction activity. Also, heating the materials similarly as for ready mixed concrete can work for CLSM in cold weather.

Less equipment needed: Equipment like loaders, rollers, or tampers are not required for placing CLSM unlike for a soil/granular backfill.

1.3.2 Challenges of CLSM

There are however challenges to using CLSM, such as:

- More research is needed on the standardization of mix designs and testing methods for different kinds of application and incorporation of various kind of wastes so as to control the production and properties for a particular project requirement.

- Any non-standard material proposed for use in CLSM is required to be characterized to ascertain its suitability for the particular application.
- Similarly new mix proportions are also required to be checked by testing fresh, hardened and long-term properties.
- High segregation, bleeding and shrinkage due to high water content and low cement in CLSMs need to be taken care of.
- The continued gain of strength by CLSM in the long-term may make its excavation difficult and involve a requirement of additional labour and cost.
- CLSM in the fresh state, being in highly flowable liquid form, is required to be placed carefully in layers to avoid hydrostatic pressure on basement walls and other such situations till it hardens.
- CLSM in deep sites need to be covered till it hardens to avoid a quick-sand like hazard.
- Underground utilities like tanks, pipes, cables etc. are required to be held in position as the same might start floating in fresh CLSM due to buoyancy.
- Care needed to be taken in case of backfilling of soft material coated pipe line to avoid scratching or damage to coatings e.g. by using high volumes of fines in the mix.
- CLSM not being a water proof material can’t be used to block leakage.
- CLSM is costly in comparison to a normal backfill, therefore may not fit a low budget project.

1.3.3 Applications

Backfill: CLSM can be easily poured in a trench, hole or cavity as no compaction is needed and this facilitates a reduced trench or excavation width. Further the uniformity and density of CLSM shall always be better than a site backfill even if properly compacted in layers. Even in the case of retaining walls CLSM would be better when allowing every layer to harden before pouring the next.

Structural fill: CLSM can be used as a foundation support and can distribute the foundation load over a larger area in case of weak soil. It can also provide a strong uniform base under a foundation slab located in a non-uniform or uneven subgrade. The thickness requirement of a foundation slab is also likely to reduce due to the strong CLSM base layer.

Insulating and isolation fill: Low density CLSM is suitable for such applications.

Pavements: Provided proper drainage, curb/gutter, storm-sewer, and gradient are ensured, CLSM can be used in pavement bases, sub-bases, and subgrades. It is not considered suitable for a base material subjected to freezing and thawing that might result in poor durability if freezing occurs after the base layer gets saturated with water. Having a poor wear-resistance, CLSM requires a wearing surface.

Conduit bedding: The flowable nature of CLSM ensures void filling beneath the pipe/conduit for electrical, telephone installations etc. to provide a proper support and thus is quite suitable for such application. While re-excavating a trench, an CLSM encased conduit can also be advantageous in terms of alerting as soon as the CLSM is struck which is different from the surrounding soil.

Erosion control: CLSM resist erosion better than other fills and used in riprap for embankment protection, spilling basins for holding rock pieces, fill flexible fabric mattresses on embankments to enhance strength and weight along-with culverts, voids beneath pavements, sidewalks, bridges etc. where erosion has removed existing granular fill.

Void: Abandoned sewers, tunnels, building basements, underground structures and mines can be conveniently filled with CLSM due to its advantage of flowability. Filling abandoned mines can ensures elimination of access, subsidence, oxygen supply for fires, acid drainage and hazardous gases release.

Nuclear facility: CLSM is advantageous over a conventional granular backfill in terms of the possibility of remote placement and decreasing human exposure to harmful radiations. CLSM can be used for encapsulation of decommissioned pipelines, waste-disposal sites, new landfill construction tanks as well as waste-stabilization.

1.4 SIGNIFICANCE OF RESEARCH

Large amounts of solid waste by-products are being generated worldwide during industrial, mining, agricultural and domestic activities, which pose environmental and ecological issues apart from requiring large quantities of land to dispose-of wastes through safe dumping. The literature reveals that with the available research-based options, the recycling/reuse potential of CKD, SFS and RHA is very low since 80 % of the total generated CKD, 70% SFS and 99 % RHA still required dumping. Thus, more research is required for evolving additional applications to reduce the huge unused quantities of the above by-products. Utilizing wastes through innovative industrial processes will lead to better use of the world's depleting existing resources by reduced extraction of virgin materials. Valuable land would also be spared for catering for reduced waste generation and the transportation cost would also be lesser for less waste handling. Reduced extraction of fresh materials shall result in lesser emissions of greenhouse gases. The construction industry consumes huge quantities of virgin materials and has potential for utilization of by-products as partial/full replacement of the virgin materials. CLSM is one such construction product that has the potential to use by-products safely since they do not have high strength and performance requirements. Along with harmless industrial wastes, CLSMs have the potential to even use hazardous wastes. In this research also, the endeavor is to use industrial by-products such as spent foundry sand, rice husk ash and cement kiln dust as construction materials for making CLSM.

1.5 GAPS IN RESEARCH AREA

CKD is reported to be used as a substitute for cement in concrete/mortar with the recommended substitution levels of only around 5-30 % (Abdulredha et al., 2021; Hussian, 2021; Singh et al., 2022). This provides limited scope for the disposal of a fraction of the total disposable quantity of CKD. Further, only a few researchers (Bassani et al., 2017; Katz and Kovler, 2004; Lachemi et al., 2010, 2008; Taha et al., 2007) have explored the use of CKD, SCMs and small or no amount of cement as binders in CLSM. Therefore, more research for maximum utilization of CKD as a replacement of cement in CLSM is required.

Spent foundry sand is generated in large quantities in metal casting process in industry. Previous researchers suggest a limited scope of use of SFS in concrete up to 20-30% replacement of natural aggregate while having mechanical and durability properties uncompromised (Ahmad et al., 2022; Prabhu et al., 2014; Siddique et al., 2018; Thiruvenkitam et al., 2020). Also, only a few researchers have studied the use of spent foundry sand as partial replacement of fine aggregate in CLSMs (Deng and Tikalsky, 2008; Dingrando et al., 2004; Naik et al., 2001; Naik and Singh, 1997a). Since CLSMs have a major proportion of fine aggregates, more research upon use of SFS as fine aggregate replacement in CLSM is required for maximizing its utilization.

RHA having around 80-95 % silica is amorphous or crystalline based upon the burning conditions (Jamil et al., 2013; Kumar Das et al., 2022) and the amorphous one is potentially used as a pozzolana (Jittin et al., 2020; Kumar Das et al., 2022). Generally, duly processed (finely ground) RHA of an amorphous nature has been used as replacement for cement in concrete with an optimum replacement level of 10-30 % (Endale et al., 2022; C. Liu et al., 2022; Siddika et al., 2021). Use of unprocessed RHA as a replacement of cement in concrete is rare (Djamaluddin et al., 2018; Makul, 2019; Sua-iam and Makul, 2013; Zerbino et al., 2011). Further, very few studies have used RHA as aggregate in concrete (Sua-Iam and Makul, 2013; Tran et al., 2021). Moreover, the literature provides only a few studies (Islam and Hossain, 2019; Nataraja and Nalanda, 2008) about utilization of RHA in CLSM. Further, a rare study (Nataraja and Nalanda, 2008) used RHA as a substitute of aggregate in CLSM that used processed RHA by grinding. Therefore, use of unprocessed RHA in as received condition was required to be explored further that would potentially widen the scope of use of RHA received from a wide spectrum of industry, with the advantage of reduced grinding and energy cost involved (Sua-Iam and Makul, 2013; Zerbino et al., 2012). Moreover, the cement content in concrete or mortar is already a small fraction of the total constituents and its replacement offers an avenue to utilize only a fraction of the total RHA generated. On the other hand, natural fine aggregates constitute a major portion of any concrete/mortar mixture and any replacement of natural aggregate could result into an adjustment of a large quantum of by-products. Keeping in mind that the CLSMs comprise a large proportion of fine/fillers, it can be a potential infrastructure solution for large scale disposal of RHA.

This study envisages the use of industrial waste by-products namely spent foundry sand and unprocessed RHA as replacement of virgin natural materials i.e. fine aggregate, and cement kiln dust as replacement of cement. Although studied individually, the combined utilization of two or more of these industrial by-products as a complete replacement of conventional constituents in the development of CLSM needed to be explored further.

1.6 OBJECTIVES OF RESEARCH

Objectives of this research are summarized as follows:

- To evaluate the utilization potential of industrial by-products and hazardous waste materials for developing CLSM.
- To investigate the engineering properties of CLSM in fresh and hardened state using these wastes either as cement or fine aggregate replacement.
- To investigate the leachability characteristics of CLSM mixes for ascertaining safety aspect of using such materials for various application.

1.7 ORIENTATION OF THESIS

Chapter 1 Introduces the concept of sustainability, role of utilization of industrial by-products in the construction industry, generation of proposed by-products namely, CKD, SFS and RHA and the related issues regarding their disposable quantum, already available disposal avenues and the need for newer techniques for large scale disposal, objectives of the research.

Chapter 2 Presents a detailed review of published literature on utilization of various by-products from different industry as constituents of CLSM and their impact upon different fresh state and hardened state properties.

Chapter 3 This chapter presents materials and methods for the experimentation. It encompasses characterization of constituent materials, describes mix proportioning for the proposed CLSM mixes and details of testing procedures followed for evaluation of the different properties in fresh and hardened states.

Chapter 4 This chapter presents the test results of properties of CLSM mixes in the fresh state and hardened states. The influence of varying proportions of by-products CKD, SFS and RHA upon fresh and hardened properties of CLSM has been discussed. Analysis of field emission scanning electron micrograph (FE-SEM) and phase identification done using X-Ray diffractogram (XRD) are also presented in this chapter. Leachate toxicity for environmental safety and ecological analysis in terms of embodied energy and embodied carbon of CLSM mixes have also been discussed.

Chapter 5 Presents the main conclusions of this research study.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

The construction industry, while recognizing the importance of sustainable development, continuously tries to evolve new technologies that help the world in its efforts towards achieving sustainability goals. CLSMs have been in the forefront in providing feasible means of safe and efficient disposal of industrial wastes and by-products by fruitfully utilizing the same in infrastructure development. A wide range of by-products from different sources have been studied for the development of CLSMs in past. CLSM studies present varied outcomes with regard to the use of input materials and by-products from various industries in terms of their impact upon the plastic and in service properties of the CLSM. Various types of materials used as binders, aggregates and as additives have an impact upon the development of CLSM or their characteristics as discussed in the following sections.

2.2 MATERIALS USED AS CONSTITUENTS OF CLSM

CLSMs are of two kinds namely, conventional and low density CLSM (LD-CLSM). Conventional CLSMs are composed of Portland cement, fine aggregate and water along with sometimes coarse aggregate. LD-CLSM are generally developed by using the same constituents required for conventional CLSM along with a foaming agent to reduce the density. Sometimes CLSMs can also be prepared by using cement, a supplementary cementitious materials like fly ash and water only, wherein fly ash acts both as a filler/fine aggregate as well as a binder. Any standardization of the constituents for CLSM could be beneficial but not obligatory (ACI 229R, 1999). The availability and cost-effectiveness and the proposed application of the CLSM are very important for the selection of mix materials. The factors guiding the choice of materials for CLSMs also impact its characteristics such as flow, strength, density, excavatability etc. In general the constituents used as the binder, aggregate and their content, water/binder ratio, additives and curing conditions influence the CLSM properties (Parhi et al., 2023). As per ACI 229R (1999), 8.3 MPa is the upper limit of unconfined compressive strength (UCCS) for a CLSM and 2.1 MPa for a CLSM to have future excavatability. The strength requirements being quite low, CLSM presents great potential for using industrial, agro based by-products in large proportions as replacement of virgin raw materials (Kaliyavaradhan et al., 2019; Ling et al., 2018a). This also helps in promoting sustainability. Various researchers have used different industrial wastes and by-products either as the binder or as fine aggregate or filler for the development of CLSM and Table 2.1 provides an overview of the same.

Table 2.1 Different by-products used in CLSM

Sr. no.	Binder	Fines/filler	Material replacement and level	Replacement effect	Reference
1.	Cement, CKD, Fly ash, Asphalt Dust	BA, Quarry waste, Crushed Sand	• Any of CKD, fly ash and Asphalt dust used + Cement • Any coarse waste	• Fly ash was best • Crushed sand best	(Katz and Kovler, 2004)
2.	Cement, CBPD	River sand	• CBPD replaces Cement, 100 %	*Cement replacement* • Compressive strength reduced • No significant change in flow	(Al-Harthy et al., 2005)
3.	Cement, CBPD, Incinerator ash, Copper slag	River sand	• CBPD, incinerator ash and Copper slag replace Cement, 100 % • Incinerator ash replaces sand, 100 %	*Cement replaced by a waste* • Compressive strength reduced • Cement along with waste best *Incinerator ash replace sand* • Compressive strength reduced	(Taha et al., 2007)
4..	Slag	Fine recycled concrete aggregate (RCA), Fine/coarse RCA	• Slag added 5-30 % of dry mass of fine RCA • Slag added 5-20 % of fine/coarse RCA	*Slag addition to Fine RCA* • Workability decreased • 20 % replacement best *Slag addition to Fine/coarse RCA* • 20 % replacement best	(Achtemichuk et al., 2009)
5.	Cement, Fly ash, Glass powder	LCD-glass sand, River sand, CA	• Glass sand replaces river sand, 0-30 %	• Workability, setting time rises • Compressive strength dropped	(Her-yung, 2009)
6.	Cement	Incineration BA, QD	• QD replaces BA 0-100 % • Cement reduction as 0.40 to 0.05 of total aggregate	*QD replaces BA* • Workability rises, setting unaffected • Compressive strength increased *Cement/Total aggregate reduces* • Setting time, w/c increased • Compressive strength reduced	(Naganathan et al., 2012)
7.	Cement, BFS	Residual soil, River sand	• BFS replaces cement, 10-30 % • Soil replaces sand	*BFS replaces cement* • Flowability and setting time increased, Compressive strength reduced *Soil replaces sand*	(Sheen et al., 2013)

				• Flowability, setting time increased, Compressive strength reduced	
8.	Fly Ash, BFS	BA	• BFS added at 10-30 % of binder • BA increased as BA/binder 1.5-3.0	*BFS added* • Flowability unaffected, bleeding reduced, Compressive strength increased *BA added* • Flowability decreased, bleeding increased, Compressive strength decreased	(Lee et al., 2013)
9.	Cement, Fly ash	Waste tire particles, Light weight aggregate from reservoir silt, River sand, CA	• Waste tire rubber replace fine aggregate 0-40 %	• Workability rises up to 20 %, setting time increase, compressive strength decrease .	(Wang et al., 2013)
10.	Cement, Fly ash	Waste oyster shell sand, River sand, CA	• Waste oyster shell sand replace river sand, 0-20 %	• Workability decrease, setting delayed • Compressive strength improves up to 5 %, reduce at higher level	(W. Kuo et al., 2013)
11.	Cement, Stainless steel reducing slag	Residual soil, River sand	• SSRS replace cement, 0-30 %	• Flow, setting time increase • Compressive strength reduced	(Sheen et al., 2014b)
12.	Fly ash (CFBC), BFS	Bottom ash (CFBC)	• BFS 10-30 % of binder • CFBC bottom ash increased, 1.5 to 3.0 times binder	*BFS increase* • Workability rises, setting time reduce, compressive strength improves *CFBC increase* • Workability reduces, setting time reduce, compressive strength better	(Park et al., 2017)
13.	Cement, Fly ash	Recycled fine aggregate from C&D waste	• Binder / Recycled fine aggregate B/R ratio 0.07-0.15 *(Binder=cement + accelerator)*	*B/R increases* • Workability rises, bleeding reduces, long term strength increase	(Zhang et al., 2018)
14.	Cement	Mine tailings, Pond ash, River sand	• Pond ash replaces sand up to 100 %	*Pond ash increase* • Settlement, compressive strength increase	(Kim et al., 2018)
15.	Cement, Fly ash	Treated oil sand waste (TOSW), River sand	• TOSW replaces aggregate, 5-10 % • TOSW replaces (fly ash + aggregate), 5-10 %	*TOSW replaces aggregate* • Water demand, bleeding reduce, compressive strength increase *TOSW replaces fly ash and aggregate* • Water demand, bleeding reduce, compressive strength reduce	(Mneina et al., 2018)
16.	Cement, Fly ash, Incinerator	Waterworks sludge,	• Sludge replaces fine aggregate, 10-20 %	• Flow reduces, setting time increase, compressive strength drops	(Fang et al., 2019)

	sewage sludge ash	Fine aggregate			
17.	Cement, Fly ash, WTS	WTS	WTS replace (FA + Cement), 20-80 %	• Workability drops • Setting time reduce up to 20-40 % WTS • 20-40 % WTS best for compressive strength	(Ho et al., 2022)
18.	Cement, RHA	Fine aggregate (sand)	Fine (150 µm) and coarse (600 µm) RHA replace cement, 40-60 %	• Water demand rise • Finer RHA better, 40 % replacement optimum	(Islam and Hossain, 2019)
19.	Cement, Fly ash, RHA	QD, River sand, RHA	Cement used with one or two waste (FA, QD, RHA, Sand)	• Small cement with large by-products, a satisfactory combination • Cement and fly ash better strength than cement and RHA • QD can replace sand	(Nataraja and Nalanda, 2008)
20.	Cement, Flyash	SFS, Flyash	SFS replaces Fly ash, 30-85 %	• Bleeding increased for high flow design mix • 30-50 % replacement optimum w.r.t. compressive strength • 85 % suit excavatable CLSM	(Naik and Singh, 1997a)
21.	Cement, Flyash	SFS, Flyash	Varying mix proportions	• Varying results • Recommended mix to start: cement (25 to 94), fly ash (334 to 463), WFS (818 to 1264), and water (291 to 504), in kg/m3	(Deng and Tikalsky, 2008)

Various CLSM properties and the impact of using different industrial and other by-products/wastes as the constituents are discussed in the following sections.

2.3 FRESH/ PLASTIC STATE PROPERTIES

Fresh state properties of CLSM like flowability, unit weight, bleeding, setting time as per penetration resistance and ball drop resistance, have been reported by different CLSM research studies and a few are discussed in the following sections.

2.3.1 Flowability

Flowability is a property that differentiate CLSM from other fills and enables the mix to self-level itself, flow into to void/cavity and compact by itself without use of any equipment. Good flowability as per ASTM D 6103 is achieved if the material from a 75 × 150 mm open ended cylinder is spread at least 200 mm in diameter without any noticeable segregation. The standard slump cone test describes flowability as low with a slump less than 150 mm, normal for 150-200 mm and high for greater than 200 mm.

Katz and Kovler (2004) investigated various properties of CLSM prepared by utilization of varying quantities of fine wastes from industry i.e., cement kiln dust (CKD), asphalt dust (AD) and coal fly ash (FA) and coarser wastes i.e., coal bottom ash (BA) and quarry waste (QW) in addition to the conventional materials i.e., cement, crushed sand and water. Water demand for a target flowability of 200 mm for all the prepared mixes was studied. Comparison of three mixes with AD, CKD, and FA each taken as fine waste at 500 kg/m^3 showed a water demand of 325, 320 and 297 kg/m^3. The shape of particles of the waste played a role in water demand of the mix, since the lower water demand, by 10 %, of an FA mix was attributed to the round shape of FA particles. The increase of fine waste from 500 to 1000 kg/m^3 causing an increase in water demand from around 320-325 to 426-457 kg/m^3 i.e., around 33-41%, led to the conclusion that fineness affects the flowability. Water demand for mixes, with BA and QW as a replacement of crushed sand respectively were 335-385 kg/m^3, 372-423 kg/m^3, and that with crushed sand itself as 320-325 kg/m^3. Higher water demand for BA and QW mixes is attributed to more porosity and fineness of BA particles mixes and to very high fineness of QW particles (22 % passing 0.075 mm sieve) in comparison to that of crushed sand. Fineness, roundness, porosity are the factors affecting flow.

Wang et al.(2013) have investigated the properties of CLSM prepared using cement, fly ash, waste tire rubber particles reduced to # 4 (size 4.75 mm) as replacement (0 - 40% by volume) of fine aggregate (FA), reservoir silt made lightweight aggregate as replacement of coarse aggregate (CA). Two groups of CLSMs named as controlled low strength rubber concrete (CLSRC) with coarse aggregate and controlled low strength rubber light weight aggregate concrete (CLSRLC) with CA completely replaced by light weight aggregate were studied. Flowability increased with addition of rubber particles up to the 20% replacement of fine aggregate in both CLSRC and CLSRLC and reduced for higher than 20 % replacement. With the addition of hydrophobic rubber particles, there is an increased water availability at the interface of aggregate and paste. It has also been highlighted that in a high water/binder mix, the level of concrete paste driving the aggregates determines the workability, which appears to have been achieved with the best driving force at an optimum level of 20 % replacement. Higher flowability reported in CLSRLC has been attributed to lower density and the round shape of reservoir silt light weight aggregate in comparison to natural CA.

Achtemichuk et al.(2009) has studied workability aspects of CLSMs prepared using only by-products i.e., recycled concrete aggregate (RCA), slag which is a supplementary cementing material (SCM). Two types of RCA, fine with 10 mm and combined fine/coarse with 28 mm maximum size, were used. The slag has been used as 5-30 % replacement of fine RCA and 5-20 % replacement of fine/coarse RCA for investigation of CLSM mixes. The results show a reduced water/binder ratio corresponding to the addition of slag. The reported slump flow for fine RCA mix ranged between 135-160 mm which increases initially from135 to 160 mm up to 20% slag and then decreases to 137 mm at 30% slag. For CLSM with fine/coarse RCA the slump values ranging between 190-210 mm were observed against an addition of 0-20% slag. By addition of fine slag, a possible improvement in particle grading resulting in better packing of the constituents potentially has spared some water to increase flow.

Naganathan et al.(2012) studied the flowability behavior of CLSM having constituents of cement as binder and industrial wastes i.e. incinerated bottom ash (BA) and quarry dust (QD) both considered as fine aggregate. Water content was controlled for a target flowability of 200±10 mm. Various mixes were prepared with varying cement contents at 8 levels from 40% to 5% of the total aggregate content and at each cement level, proportioning of BA/QD was varied by 25 % in the aggregates into five combinations i.e., 100/00, 75/25, 50/50, 25/75 and 00/100. It was observed that the w/c requirement for the desired slump flow increased with increasing BA in the aggregate mixture. The study has also examined a relationship for flowability between BA/QD, water/cement (w/c) and cement/total aggregate (c/TA) of the CLSM mixes and found that higher w/c is negatively related to c/TA. Further, w/c is maximum for BA/QD of 100/00 and minimum for 00/100. It was concluded that addition of QD lowers the w/c requirement. A possible reason could also be more fineness of BA in respect of FM and percentage finer than 0.075 mm size in comparison to QD.

Her-yung (2009) investigated the flow characteristic in terms of normal slump due to the effect of adding waste LCD glass-sand as replacement of normal sand in CLSM mixes that also had other additional constituents such as cement along with fly ash and glass powder each at 10 % of the cement as binders and coarse aggregate. Water/binder varied as 1.1, 1.3 and 1.5 to form three groups and each mixture group had 4 levels with glass sand replacing the fine aggregate at 0, 10, 20 and 30 % levels. Slump flow values ranging between 200–210 mm, 220–230 mm and 230– 250 mm respectively for w/b 1.1, 1.3 and 1.5 were observed which had a rising trend with addition of glass-sand in replacement of sand and termed as having a high fluidity property. Higher slump flow might be due to coarser glass-sand particles (FM=3.37) with much less water absorption (0.45%) compared to finer normal sand (FM=2.73) with water absorption (1.5%) leaving surplus water in the mix. Finer particles have a higher surface area needing more water to cover their surface.

Lachemi et al.(2008) studied CLSM having varied content of the constituents, cement along with cement kiln dust (CKD) from four different sources as binder, natural sand. Some mixtures were also prepared using only CKD as binder. In the CLSM mixes, CKD was added as 4-45 % of the total constituents and the required water/binder (w/b) ranging between 0.6-1.9 was arrived at for the desired slump flow of around 400-550 mm. Comparison of the two CLSM mixes with the same w/b=0.6 and cement content of 2%, showed a reduction of slump flow from 420 mm to 0 upon increasing the CKD content from 30% to 45%. Similarly for other two mixes having no cement and with w/b= 0.7, a CKD increase from 30 to 45% caused the slump flow to reduce from 535 mm to 475 mm. Thus, it was concluded that addition of CKD reduced the flowability which was attributed to water affinity of CKD raising the water demand to maintain the desired flowability in CLSMs both with or without cement.

Lachemi et al.(2010) studied the use of CKD and blast furnace slag in the development of CLSM and observed the flowability behavior by varying their content in the mix. With a fixed water content at 341 kg/m^3 and CKD at 200 kg/m^3, an increase in slag from 40 to 100 kg/m^3 caused a rise in flowability from 210 to 245 mm which however decreased to 230 mm with further increase in slag content above 100 kg/m^3 up to 300 kg/m^3. Therefore, it was concluded that rise in slag content up to 100 kg/m^3 enhanced the flow and at higher slag content the reduction in flow was due to the water affinity of slag. Further, the comparison of two sets of mixes was done and it was also observed that, for a given flow range of 205-245 mm, the increase in CKD content from 200 kg/m^3 (in the first set) to 300 kg/m^3 (in the second set) resulted in enhanced water requirement from 341 kg/m^3 to 361 kg/m^3 leading to the conclusion that flow depended upon the CKD content in the mix.

Nataraja and Nalanda (2008) in a study of performance of industrial by-products such as fly ash, RHA, QD in CLSMs, the flow characteristics and the factors affecting them were studied. Additionally varied quantities of cement as binder, sand and water were also used in the formulation of the mixes. Flowability at range of 175-225 mm was studied against a w/c ratio for cement-fly ash and cement-RHA mixes in the range of 1:5 to 1:25, cement-fly ash-sand and cement-RHA-sand mixes for the range of 1:6:25/50 to 1:12:25/50 and cement-sand and cement-QD mixes for ranges of 1:12.5 to 1:50. It was observed that the flowability rose steeply from 175-287 mm with a change in w/c from 2-2.5 for cement-Fly ash 1:5 mix. Similarly, flowability rose from 175-350 mm with a change in w/c from 6-7 for cement-RHA 1:5 mix, from 160-275 mm with a change in w/c from 3-6 for cement-sand 1:12.5 mix and from 175-275 mm with a change in w/c from 2.5-4.5 for cement-QD 1:12.5 mix. With similar flowability patterns for other mixtures also, it was concluded that flowability increased with increased w/c ratio with any type of by-products. The study of the above flow observations against w/c also intimated that the mixtures containing fly ash resulted in desired flowability for a lower w/c as compared to RHA. The high sphericity of fly ash particles and high porosity of RHA could be the reasons for this. Similarly, the required flow for mixes with QD could be achieved with lower w/c in comparison to sand. The study also examined the variation of w/c ratio against the percentage of by-products like fly ash, RHA, QD as well as sand in the mix for flows of 175 mm, 200 mm and 225 mm. A positively correlated linear trend between w/c and the percentage of by-product in the mix was observed.

Kuo et al.(2013) studied the flow characteristics of CLSM containing waste oyster shells (WOS) added as 0-20 % replacement of natural fine aggregate. Other constant constituents were cement at 160 kg/m^3, fly ash 40 kg/m^3, coarse aggregate 400 kg/m^3 and w/b of 1.3. With addition of WOS as 20 % as replacement of fine aggregate, all the parameters of flowability such as the slump, slump flow and tube flow of the CLSM decreased from 26.5 to 21.5 cm by 19 %, from 60 to 41 cm by 32 % and from 21 to 15 cm by 28.5 % respectively. Decreased workability was attributed to a higher water-absorption at 7.66 % of WOS against 2.2 % for fine aggregate which adsorbs water and leaves less water in the mix for flow. Another reason was fineness of the WOS as per its FM=2.0 against FM=3.2 of fine aggregate, and consequently the increased surface area needed more water to cover the particles with less water left for flowability of the mix.

Sheen et al.(2013) in a study of CLSM to evaluate the suitability of surplus soil from trenches and GGBFS as constituents examined the flowability characteristics in respect of tube flow. Soil was used in combination with sand in three sand:soil ratios of 6:4, 5:5 and 4:6 and, for each ratio, the slag was added from 0-30 % of cement. For addition of slag from 0-30 %, the tube flow increased from 156-223 mm (43 %), 161-245 mm (52 %) and 187-270 mm (44 %) in three sand:soil ratio groups. With w/b kept as constant, the slag addition increased the flowability which was attributed to reduced size and volume of voids in the mix as well as retardation of the process of early age ettringite formation. Also, the addition of cohesive soil in the mix caused higher flowability as the group of sand:soil ratio 4:6 observed the highest flow range (187-270 mm). Sheen et al. (2014b) in another study of CLSM having a fixed sand/soil ratio of 6/4 and with an addition of 0-30 % stainless steel reducing slag (SSRS) as replacement of OPC and varying w/b at 3.4, 3.6 and 3.8 for three groups, attributed the enhanced flowability to the latent nature of SSRS retarding the ettringite formation at early age, the reduced size and volume of voids due to presence of SSRS. Mixes with higher water content or w/b also showed enhanced flow. Sheen et al. (2014a) in the study of CLSM by adding fly ash (FA) as 0-45 % replacement of OPC, again attributed increased flowability to the retardation of ettringite formation at early age.

Lee et al. (2013) studied the flowability characteristics of cementless CLSM mixes using fly ash and slag as binders and bottom ash as fine aggregate along with solid NaOH as alkali activator for binders. The water/binder, slag/binder, bottom ash/binder, and NaOH/binder ratios were variables. The flow testing results after 1 hour with a slag content as 10, 20 and 30 % of the binder were 160 mm which suggested that the addition of slag had little effect on flow. However, the reduction of w/b from 0.67 to 0.58 resulted in the reduction of flowability from 200 to 150 mm. Flowability of 160 mm, 210 mm, 180 mm and 200 mm for NaOH content at 1.5 %, 2.5 %, 3.5 % and 4.5 % of the binder content showed an increased flowability with increasing NaOH content in the mix. With 200 mm, 130 mm, and 80 mm flow for bottom ash/binder ratio of 1.5, 2.5 and 3.0 it was concluded that addition of bottom ash reduced flowability attributed to its high absorption of 5.45%.

Park et al. (2017) in a study of CLSM investigated the flow characteristics by varying the contents of circulating fluidized bed combustion (CFBC) fly ash, blast furnace slag (as binders), CBFC bottom ash (as aggregate), water content and NaOH (as alkali activator). The flow decreased from 229 mm to 180 mm for increasing the NaOH concentration from 2 % to 6 %, which was attributed to increased viscosity due to higher NaOH content. An increased water content factor from 1.3 to 1.7 (with respect to CFBC fly ash binder) enhanced the flowability by 109 % in line with the general trend. Increasing the aggregate content (CFBC bottom ash with respect to binder) from 1.5 to 2.5 caused the decrease in flowability from 283 mm to around 220 mm. As far as the effect of slag content was concerned, the addition of slag content from 0.1 to 0.3 times of the CFBC fly ash caused a slightly decreased water demand. This was attributed to the high absorption capacity of fly ash which gets reduced by an increase of slag in the mix and thus more water available in the mix. Also, because of the higher specific gravity of slag compared to CFBC fly ash, the replacement of fly ash by slag resulted in a lesser volume along with more water in the mix that enhanced flow.

Alizadeh (2019) investigated the effect of volumetric ratios such as; volume of paste (cement + SCM + water) to total mix volume as paste volume ratio (PVR), Portland cement to cementitious materials ratio (as pc/cm), water to solids ratio (as w/s) and by weight ratio of water to cementitious material (w/cm) upon the flowability of CLSM mixes comprising cement, fly ash, sand and water. With pc/cm ratio fixed, an increased PVR enhanced the flow which was prominent after PVR of 0.40. This was attributed to the fact that aggregates being the major part of CLSM mix need water to cover surface, absorb and separate its particles for flow, and with higher PVR the volume of aggregate gets reduced and needs less water for separation of its particles and thus higher flowability. Given the fixed PVR, an increased w/cm ratio resulted into higher flow and also the effect is pronounced when the PVR is higher, possibly due to the fact that addition of water in paste decreased its consistency resulting in a higher flow. The increase in pc/cm ratio lowered the flow, which was attributed to an increased cement and a reduction of fly ash having spherical shaped particles, which increased interparticle friction of the mix constituents. Higher w/s ratio also resulted into higher flow linearly and was considered as a parameter for estimating the mix flow.

Zhang et al. (2018) studied the effect of water to solids ratio (W/S), accelerator to binder ratio (A/B) and binder to recycled fine aggregate ratio (B/R) upon the flowability of CLSMs. OPC, a sulfoaluminate cement clinker-based accelerator, recycled fine aggregate from construction and demolition waste, and fly ash were the constituents. The flowability remained unaffected by the A/B ratio and increased with increase in W/S ratio and B/R ratio. Availability of increased free water in the mix with increased W/S ratio from 0.27 to 0.30 was cited to be reason for higher flowability. With a rise in B/R from 0.07 to 0.15 the flowability increased from 195 mm to 220 mm. Due to the higher binder content the fine aggregate gets reduced relatively in the mix and further the increased cement paste would wrap the rough fine aggregate particles, and retain more water which resulted in higher flow.

Mneina et al.(2018) investigated flowability of the CLSMs using treated oil sand waste (TOSW) as 5-15 % replacement of fine aggregate. The addition of TOSW caused a lower water demand by up to 25 % to achieve the desired flow. Incorporation of finer TOSW resulted into better packing leading to release of water trapped in voids between larger cement and aggregate particles and further very fine TOSW acting as a lubricant reducing the interference between other constituents, were cited as the reasons for higher flow.

Qian et al.(2019) investigated the flowability of CLSM mixes in terms of water demand for a flow of 260mm by using excess excavated soil as replacement of sand. The water demand of 38.6% increased to 48% due to decreasing the sand/soil ratio from 0.43 to 0. The primary reason for the above was reported to be the fineness of soil particles providing a higher surface area resulting in absorption of more water for required flow.

Do et al. (2019) investigated flowability of CLSM mixes using fly ash (Fa), red mud (Rm), lime (L) and gypsum (G) as a cementless binder as Fa-RmLG along with pond ash as fine aggregate. Varying factors were G/Rm, Fa/RmG, L/RmG for testing different properties of the mixes. With other factors remaining unchanged, the mixes with addition of gypsum represented by G/Rm at 0.40, 0.75, and 1.33 showed good flowability in the range of 200 mm which however decreased to around 145 mm and 110 mm for higher ratios of G/Rm ratio of 2.5 and 6 respectively. This phenomenon was related to very drastic gypsum addition compared to red mud in the binder, which upon mixing with water quickly converted from hemihydrate to dihydrate form, creating a need for more water in the mix for maintaining the desired flowability. This resulted in reduction of flowability with high gypsum addition. Similarly, slight reduction of flowability from 275 mm to 220 mm was observed for the increased fly ash factor Fa/RmG from 1.29 to 2.14, that remained unchanged even when the factor was raised 2.14 to 3. With increase in lime content in terms of factor L/RmG from 0.14 to 0.71, a slight reduction in flowability 250-200 mm was witnessed. Also, in both the above cases a reduced water content was observed in mixes for higher Fa/RmG and L/RmG factors, that possibly related with reducing flowability.

Ho et al. (2022) studied the flowability characteristics due to varying contents of alkali accelerator, waste water sludge and water/binder ratio in CLSM mixes comprising waste water treatment sludge (WTS), NaOH, fly ash, and OPC. The w/b as the ratio of sum of water and NaOH solution to sum of binders (WTS, OPC and fly ash) at 0.5, 0.65 and 0.80 and sludge content of 0, 20, 40 and 80 % of the sum of OPC and fly ash, whereas alkali accelerator (A) at 0, 3, 5 and 10 % as ratio of Na_2O (in NaOH solution) to the sum of the binding materials (WTS, OPC and fly ash) were considered. A relation of higher slump and slump flow with higher tube flow was observed. Tube flow decreased ranging between around 35-56 % with an increase in alkali accelerator (A) between 0 to 10 % in the mixes, which was due to alkalis accelerating the cement hydration leading to a reduction of workability. The addition of WTS from 0 to 80 % also caused a reduction of workability in terms of decreased tube flow between 24-0, 15.5-0, 10.5-0 cm for mixes having A values of 0, 3 and 5 % respectively with w/b 0.50 and similar results for other w/b ratios also. This reduction was due to the irregularity of WTS particles reducing the lubrication effect and the high specific surface area of WTS particles absorbing more water from connected pores leaving less water in the mix for facilitating flow. Similarly, Hwang et al. (2017) in another study of CLSM containing WTS, GGBFS, FA and NaOH activator have also reported a decreased flowability for increased WTS content for the reasons of irregularity of WTS particles and the high absorption capacity for reduction of workability.

2.3.2 Bleeding

Katz and Kovler (2004) studied the bleeding behavior of the CLSM mixes having industrial by-products such as fine wastes i.e., cement kiln dust (CKD), asphalt dust (AD) and coal fly ash (FA) and coarser wastes i.e., coal bottom ash (BA) and quarry waste (QW). Bleeding values noticed were in descending order for FA, AD and CKD mixes irrespective of the quantum of crushed sand in the mix i.e., 500 or 1000 kg/m^3. The highest bleeding for the FA mix was attributed to the sphericity of the FA particles and delayed setting. Early thickening of the CKD mix due to its cementing capacity was quoted as the reason for minimum bleeding.

Naganathan et al. (2012) studied the stability by evaluation of bleeding of the CLSM comprising cement as binder and industrial wastes i.e. incinerated bottom ash (BA) and quarry dust (QD) both considered as fine aggregate in varying proportions. The stability or bleeding values observed were in the range of 1.7 %-5.3 %. Higher bleeding was observed for BA/QD at 100/0 and lesser for 0/100. Further, the effect of w/c and c/TA upon bleeding values was also studied and it was concluded that bleeding increases with higher w/c while decreases with higher c/TA. A higher cement content, related to higher c/TA, shall need more water for hydration that leaves less surplus water in the mix to augment bleeding. With a higher w/c availability of extra water above hydration requirement results a higher bleeding. Addition of QD caused lesser bleeding due to the fact that such mixes needed lesser w/c for a specified flowability. Thus, lesser w/c would lead to reduced bleeding.

Naik and Singh (1997a) investigated bleeding of flowable slurries made using clean sand (FS1) and used foundry sand (FS2) as partial replacement of two types of Class-F fly ashes (F1 and F2) along with cement. Both kinds of foundry sands, clean and used, were added at 30, 50, 70 and 85 % as replacement of fly ash in two sets of mixes i.e., one set for each fly ash F1 and F2. Cement content at round 40 kg/m^3 was used in each mix. The quantity of F1 fly ash was also more than the F2 fly ash in their respective mixes. Target flowability for F1 mixtures was 406 ± 25 mm and for F2 as 279 ± 50 mm. It was observed that at early age (1h), all mixtures with fly ash (F1) showed the depth of bleeding water ranging between 1.8-17.8 mm in comparison to 0-3.3 mm i.e., almost no bleeding, for fly ash (F2), which was attributed to the lower fineness of F1 fly ash along with high water content (in terms of higher target flow) in the mixtures. Notably except 85 % foundry sand mixes, F2 fly ash mixtures with lesser percentages of foundry sand did not show any bleeding. Bleeding also increased with increase in foundry sand content that replaced the fly ash, which was attributed to increased voids by coarser foundry sand than the fly ash.

Lachemi et al. (2008) studied the bleeding of CLSM mixes prepared using cement along with cement kiln dust (CKD) from four different sources as binder where natural sand was fine aggregate. Four mixes with 4, 10, 15 and 30 % of the total mix materials as CKD content were examined. Bleeding values range between 3.1-5.8 %, 0.8-1.0 %, 0.2-0.8 % and 0-0.2 % respectively for mixes with 4, 10, 15 and 30 % CKD content from four different sources. It was seen that bleeding reduced sharply with increasing CKD content from 4 to 30 %. It was also notable that the bleeding reduced with CKD irrespective of the source. Reduced bleeding was stated as a beneficial effect as bleeding is always a matter of concern due to high water content in CLSMs. It may possibly be again attributed to CKD's water affinity requiring more water for achieving required flowability.

Lachemi et al. (2010) in a study of utilizing CKD and blast furnace slag in CLSM observed the decreased bleeding from 3.5 % to 1.10 % for increase in slag content from 40 to 300 kg/m^3, while the other constituents i.e., water content at 341 kg/m^3 and CKD at 200 kg/m^3, were fixed. Further the mixes with CKD at 300 kg/m^3 showed a lesser bleeding level of around 1% even when water demand was higher at 361 kg/m^3 and also increasing the slag content from 20 to 45 kg/m^3 did not affect the bleeding as it remained around the 0.85-0.90 %. Less bleeding at higher levels of CKD has been attributed to its cementing capacity causing thickened mixes at early age.

Wang et al. (2013) studied the effect of addition of waste rubber aggregate as replacement of fine aggregate upon bleeding in CLSM. It was observed that the total bleeding increased with an addition of tire rubber aggregate up to 20% replacement level. At higher than 20% rubber particles, a slightly reduced bleeding was reported, which is attributed to enhanced pores caused by rubber particles. It has been suggested that the increased addition of irregular surfaced rubber particles delays their settlement in the mix. This possibly slowed the release of water in mix leading to reduced bleeding even with relatively higher water/binder ratio of the CLSM mixes.

Sheen et al.(2014a) in a study of CLSM examined the bleeding property due to the addition of fly ash (FA) as 0-45 % replacement of OPC in 3 groups of mixes with w/b as 5.0, 3.2 and 3.2 along with binder content (PC+FA) at 80 kg/m^3, 100 kg/m^3 and 130 kg/m^3. The bleeding increased with the addition of FA (0-45%) in the three binder groups as (4.64-10.81) 232 %, (5.02-11.26) 224 %, (6.13-11.61) 189 %. Higher bleeding with FA addition was attributed to its latent nature leaving more water in the mix for bleeding.

Lee et al. (2013) in the studied bleeding of cementless CLSM mixes using fly ash and slag as binders and bottom ash as fine aggregate along with solid NaOH as alkali activator for binders, with water/binder, slag/binder, bottom ash/binder, and NaOH/binder ratios as variables. With slag content at 10, 20 to 30 % of the binder, bleeding was 0.04 %, 0.0225 % and 0.011 %. It showed that addition of slag reduced bleeding which was attributed to higher hydration character of slag causing a reduction of unreacted water in the mix. A rise in bleeding by 50 % due to higher w/b of 0.67 compared to 0.58 is attributed to excess water than needed during hydration. Increase in bottom ash/binder ratios from 1.5 to 2.5 and 2.5 to 3.0 causing 140 % and 22.2 % rise in bleeding was attributed to higher water content, required for flowability, which acted as excess water than needed for hydration and added to bleeding. Addition of NaOH had less influence than bottom ash and slag on bleeding.

Park et al. (2017) investigated the bleeding behavior of the CLSMs due to variation of the content of CBFC bottom ash (as aggregate), water content and NaOH (alkali activator). It was observed that the increased NaOH from 2 to 4% in the mixes decreased the cumulative bleeding by 71 % (0.41 to 0.12 %), which was attributed to enhanced viscosity of the mixes. Increased water content from 1.5 to 1.7 increased the bleeding from 0.12 to 3.26 %. Enhancing the CFBC bottom ash from 1.5 to 2.0 resulted in to increased bleeding from 3.26 to 4.34 %. For a fixed water content in the mixes, this was attributed to the rough surface of the aggregate particles that entrapped the water during the preparation which is released later after placement of the mix. The effect of water and bottom ash in enhancing the bleeding was pronounced compared to that of NaOH reducing the bleeding.

Mneina et al. (2018) in a study of CLSMs with addition of TOSW as replacement of fine aggregate by 5-15 % reported a reduction of bleeding by 76-100 % for mixes having some fly ash and 17-70 % for the mixes with even fly ash also replaced by TOSW, in comparison to the control mixes with 0 % TOSW i.e. 100 % fine aggregate. The addition of TOSW having large fines i.e., have more surface area, needed more water to cover their surface which is held and prevented from escaping to surface during the setting of mix.

2.3.3 Fresh state Unit weight

Katz and Kovler (2004) in a study of CLSM mixes having industrial by-products such as fine wastes i.e., cement kiln dust (CKD), asphalt dust (AD) and coal fly ash (FA) and coarser wastes i.e., coal bottom ash (BA) and quarry waste (QW) reported a lower fresh unit weight of around 1850 kg/m^3 for the CLSM mix with BA as aggregate against around 2200 kg/m^3 of the mixes with other coarse aggregates i.e., CS or QW regardless of the dusts used. Reduced unit weight was attributed to the porous nature of the BA as compared to CS and QW.

Her-yung (2009) investigated the effect of adding waste LCD glass-sand as replacement of normal sand in the unit weight of CLSM mixes having cement, fly ash, glass powder along with coarse aggregate as other constituents. The unit weight values of the CLSM mixes ranged between 2173-2186 kg/m^3 for w/b=1.1, 2163-2170 kg/m^3 for w/b=1.3 and 2131-2136 kg/m^3 for w/b=1.5. The unit weight also reduced with the addition of glass-sand in replacement of sand within the group. This is possibly due to lower relative density of 2.42 of glass-sand against 2.63 of normal sand. The maximum unit weight observed is less than that of a normal concrete, which is attributed to much less cement content at just 10% of the fine aggregate and only the aggregates constituting the matrix that made a loose structured mix and lesser density of aggregates.

Wang et al. (2013) in their study of CLSM added the waste tire rubber particles at varying replacement (0 - 40% by volume) of fine aggregate (FA) for two groups using different coarse aggregates, firstly with normal coarse aggregate (CA) designated as CLSRC and secondly with reservoir silt made lightweight aggregate named CLSRLC. It has been reported that the range of fresh unit weight of both groups was below 2100 kg/m^3 due to the impact of incorporation of lower density rubber particles in replacement of normal fine aggregate. An average 69 kg/m^3 drop in unit weight for every 10 % increase in replacement level has been reported attributable to the 1.5 times lower specific gravity of 1.0 of rubber aggregate against 2.7 of normal fine aggregate. Further the unit weight range of the CLSRC group of 1784–2060 kg/m^3 is also higher than the range of 1591–1868 kg/m^3 for CLSRLC, which is due to replacement of heavier material i.e., coarse aggregate with higher specific gravity 2.6 by a lighter material reservoir silt lightweight aggregate having a lower specific gravity of 1.4.

Naganathan et al. (2012) studied the effect of using varying quantities of aggregates i.e., industrial waste incinerated bottom ash (BA) and quarry dust (QD) in combinations of 100/00, 75/25, 50/50, 25/75 and 00/100 percent and the cement/total aggregate (c/TA) ratio varying between (0.40 to 0.05), upon the fresh unit weight of the CLSM mixes. It has been observed that the fresh unit weight is a maximum for BA/QD of 00/100 and minimum for 100/00. It can be inferred that addition of QD increases the unit weight of CLSM. Also, the fresh unit weight is seen to be positively related to c/TA ratio. Higher unit weight can be attributed to denser QD (specific gravity = 2.59, bulk density=1720 kg/m^3) compared to BA (specific gravity = 1.83, bulk density = 964 kg/m^3). Also, the higher density in CLSM with higher c/TA was due to cement (normal specific gravity = 3.14) being denser than both the aggregates.

Sheen et al. (2013) in a study of CLSM to evaluate the suitability of surplus soil from trenches, with GGBFS as constituents observed the fresh unit weight range of 2091-2095 kg/m^3 for different mixes, which was having a minor variation. It was concluded that the sand:soil ratio variations (6:4, 5:5 and 4:6) or addition of slag as replacement of cement (0-30%) did not have much effect upon the unit weight. This was attributed to the fact that specific gravity of sand and soil as 2.66 and 2.69 were very close and these constituted the bulk of the mix. The content of cement/slag being very low in the mix, therefore, variation of cement and slag having nearby specific gravities of 3.15 and 2.89, was not reflected in the unit weight.

Mneina et al. (2018) in a study of CLSMs with the addition of TOSW as a replacement of fine aggregate by 5-15 % reported a reduction of fresh unit weight ranging between 2190-2195 kg/m^3 to 1816-1942 kg/m^3 i.e., by 17 % for the mixes compared to the control mixes without TOSW. This was attributed to the lower specific gravity 2.23 of the TOSW compared with that of the replaced fine aggregate.

2.3.4 Setting time (Penetration resistance)

Setting time of CLSM is an important parameter to ascertain the degree of hardness achieved for allowing desired loading. The setting time is evaluated by measuring resistance offered by a stiffening CLSM mix to the standard needle against its penetration by 25 mm into the surface (ASTM C403, 2008). Alongwith the penetration resistance of 3.4 MPa and 27.6 MPa cited to be corresponding to initial and final setting time as per ASTM C403, many researchers have also considered different values for evaluation of the setting times in their studies. Setting time is very siginificant for a CLSM in the sense that it decides the type of project the CLSM would be suitable for.

Katz and Kovler (2004) studied the setting time of the CLSM mixes for achieving a penetration resistance of 0.69 MPa. Quantities of industrial by-products such as fine wastes i.e., cement kiln dust (CKD), asphalt dust (AD) and coal fly ash (FA) and coarser wastes i.e., coal bottom ash (BA) and quarry waste (QW), were varied for the study. With CS being the aggregate, and around 500 kg/m^3 of fine waste, the setting time for FA mixes remained unchanged at around 15 hours for varying cement contents from 50 to 100 kg/m^3 and for AD and CKD mixes, setting times reduced from around 30 hours to 18 hours. The setting process was governed mainly by hydration of cement in AD/CKD mixes leading to reduced setting time for higher cement content. However, the setting process was dominated by the contribution of FA in the FA mixes because setting time was unchanged for higher cement contents. With twice the quantum (1000 kg/m^3) of fine wastes the setting times got slightly extended from 15 and 32 hours to around 20 and 45 hours for the FA and CKD mixes respectively. A steeply increase in setting time from 30 to 160 hours in AD mix was attributed to its complete inertness. Replacement of CS by BA resulted in shortening of setting time for AD mixes from 30 to 8 hours and CKD mixes from 32 to 20 hours attributed to the contribution of BA in setting. Replacement of CS by QW increased the setting times in AD mixes from 30 to 45 hours and in CKD mixes from 33 to 45 hours attributed to the inertness of QW similar to AD.

Lachemi et al. (2008) in a study of CLSM, also examined the effect of CKD addition upon the initial and final setting time as per ASTM C403 (2008). The initial setting time of the four mixes designated as mix-1, mix-3, mix-8 and mix-10, with CKDs from four different sources, added at 4, 10, 15 and 30 % were checked. Mix-1 had initial and final setting time ranging between 11-17 and 19-27 hours, mix-3 had 14-31 and 25-43 hours, mix-8 had 32-95 and 63-127 hours and mix-10 had 30-74 and 50-123 hours. Both initial and final setting times were higher for mix-3 in comparison to mix-1. The increased setting time was attributed to the reduction of cement from 4 % in mix-1 to 2 % in mix-3, possibly because cement undergoes faster hydration leading to early strength gain. Similarly mix-8 also showed higher setting times than mix-3 and mix-1 possibly due to the lack of cement.

Lachemi et al. (2010) studied the setting time as per ASTM C403 (2008) of the CLSM mixes prepared using varying contents of CKD and blast furnace slag as binders. Mix-1 having cement at 40 kg/m^3, no slag and CKD at 200 kg/m^3, clocked initial and final setting time of 21 hours and 43 hours. Mix-8 with no cement, no slag, and CKD at 300 kg/m^3 showed initial and final setting time of 28 hour and 52 hours. The delayed setting time in mix-8 was attributable to the lack of cement even when the CKD content was higher. For a set of mixes mix-2 to mix-7 with CKD at 200 kg/m^3, increasing the slag content from 40 to 300 kg/m^3 reduced the initial and final setting time from 37 to 28 hours and 72 to 65 hours. Hydration of slag with pozzolanic and hydraulic properties were said to be reason for the reduction of setting time. For another set of mixes with CKD at 300 kg/m^3, the increase of slag from 20-45 kg/m^3 did not affect the initial and final setting time much as the ranges were 25-28 hours and 51-57 hours respectively. However, lesser setting times for CKD at 300 kg/m^3 mixes compared to CKD 200 kg/m^3 mixes was attributed to CKD's high absorption capacity resulting in reduced consistency of the mixes instead of rapid setting.

Wang et al. (2013) has shown that the initial setting time increased by around an average around 35-40 minutes for use of each 10% waste tire rubber particles as replacement of natural fine aggregate for both the CLSMs i.e., using normal coarse aggregate designated as CLSRC and using reservoir silt lightweight aggregate as the replacement of coarse aggregate named as CSLRLC. Increasing rubber particles due to their hydrophobic nature possibly have spared more water in the mix leading to increased setting time. Moreover, rounded shape and light weight of the reservoir silt lightweight aggregates in the CLSRLC group also led to enhanced workability and a prolonged setting time at high water/binder ratio.

Naganathan et al. (2012) investigated the setting time for achievement of a desired strength level to resist a particular loading condition. The effect of varying BA and QD in aggregate combination (BA/QD) and cement to total aggregate ratio (c/TA) upon setting time was examined in the CLSM study. The CLSM was prepared with cement as binder, BA and QD combined as aggregates. Significant levels of strength were corresponding to penetration resistance of 0.344 MPa and 2.758 MPa as observed by penetration of a standard needle in to the stiffening CLSM. The time taken from mixing the water in the CLSM till its achievement of penetration resistance of 0.344 MPa is termed as the initial setting time and this strength is considered suitable for allowing human foot loading. The level of strength to achieve penetration resistance of 2.758 MPa is considered suitable as the threshold for vehicular loads. Researchers have reported the initial setting time ranging between 3.7-8.5 hours for allowing human loading and time range of 5.4-44.5 hours suitable for threshold for vehicle loads. Investigation of the effect of w/c upon initial setting time revealed an obvious enhancing effect and further as the w/c is more for higher BA than QD it can be related to addition of BA. It is also observed that setting time decreased with increasing c/TA which is possibly due to the fact that a mix having more cement content would set earlier.

Her-yung (2009) reported that in CLSM using waste LCD glass-sand increasingly replacing natural sand caused longer initial setting time. The observed ranges of setting time 372-463, 392-512 and 456-566 minutes are for an addition of glass-sand from 0-40 % in respect of mixes with w/b of 1.1, 1.3 and 1.5 respectively. The increase in setting time has been 24.4 %, 30.6 % and 24.1 % due to 40 % addition of glass-sand in the CLSM in the three w/b groups. The setting time with higher w/b has also increased. The reason for this increase in initial setting time probably is that surplus water available in the mix is either due to less absorption (0.45%) of glass-sand compared to 1.5% of natural sand or due to higher w/b.

Kuo et al. (2013) studied the setting behavior with penetration resistance test of CLSM containing waste oyster shells (WOS) added as 0-20 % replacement of natural fine aggregate. The setting time for achieving a penetration resistance of 2.74 MPa was considered appropriate for allowing construction. The setting time with WOS addition at 0-5 % increased from 210 to 260 minutes (around 3-5 hours appropriate for early strength CLSM) and from 10-20 % from 330 to 465 minutes (around 12-36 hours appropriate for general CLSM). The increased setting was attributed to high porosity of WOS that absorbs more water and postponed hydration. Also, the culturing of oysters in sea water increased organic matter in them, which hampered hydration and delayed setting.

Sheen et al.(2013) in a study of CLSM using surplus soil and GGBFS as constituents examined setting time, for the penetration resistance of 2.74 MPa, of the mixes prepared with three sand: soil ratio variations (6:4, 5:5 and 4:6) and the addition of slag as replacement of cement (0-30%). For three sands: soil ratios, with the addition of slag from 0-30%, the setting time increased from 13.4 to 18.1 hours i.e., by 33 %; from 14.3 to 18.9 hour i.e., by 35 %; and from 15.1 to 25.0 hours i.e., by 66 % respectively. Increased time for addition of slag was attributed to an associated reduction of cement (by replacement) that has a better binding property than a latent material slag. Higher soil content in aggregate also caused a delayed setting seen in a sand: soil 4:6 ratio with highest setting time range (15.1-25.0 hours), attributed to higher cohesive soil delaying the hardening process due to obstructing the capillary water release.

Sheen et al. (2014b) in another work studied the setting time by penetration resistance procedure of the CLSM having fixed sand/soil ratio of 6/4 and with an addition of 0-30 % stainless steel reducing slag (SSRS) as replacement of OPC, with varying w/b at 3.4, 3.6 and 3.8 forming three groups. The setting time increased for addition of SSRS (0-30%) by 24.1 %, 18.8 % and 62.0 % in the three binder groups and setting time also increased by 2.25 % with change in w/b from 3.4 to 3.6 and by around 30 % for w/b from 3.6 to 3.8. Enhanced setting time was attributed to decreasing content of OPC by SSRS addition.

Sheen et al. (2014a) in a study of CLSM examined the setting time due to addition of fly ash (FA) as 0-45 % replacement of OPC in 3 groups of mixes with w/b as 5.0, 3.2 and 3.2 along with binder content (PC+FA) at 80 kg/m^3, 100 kg/m^3 and 130 kg/m^3. The setting time increased with the addition of FA (0-45%) in the three binder groups as (32-38.8 hours) 21.2 %, (27.5-31.8 hours) 15.6 % and (16.8-23.3 hours) 38.7 %. The enhanced setting time with FA addition could be attributed to its latent nature. However, with increased binder content the setting time decreased which was attributed to a rise in OPC in mixture giving it early strength.

Park et al. (2017) investigated the setting time of the CLSMs due to variation of the content of slag, CBFC bottom ash (as aggregate), water content and NaOH (alkali activator). The setting time to achieve a reference penetration resistance of 3.45 MPa, decreased from 127 to 78 hours due to increasing the NaOH from 4 to 6 % and increased from 107 to 127 hours for changing the water content from 1.5 to 1.7. Also, the increased aggregate i.e., CFBC bottom ash content from 1.5 to 2.5 times the binder, caused a decrease in setting time from 127 to 74 hours and for enhancing the slag content from 0 to 0.30 times of CFBC fly ash, the time decreased from 107 to 22 hours. Except water, the setting time decreased with increased aggregate, slag and NaOH. Easier leaching of calcium, silicon and aluminum from the slag leading to creation of CSH with alkali activation and gain of strength, was stated to be the reason for reduced setting time. Similarly leaching of calcium from CFBC bottom ash containing lime sources, like $CaSO_4$ and lime, in the presence of weak alkaline solution (NaOH solution molarity 1) was the cause of quicker setting. Higher NaOH in the mix enhanced the fly ash reactivity, thereby led to shortened setting time.

Wang et al. (2018) studied the stiffening time as per penetration resistance procedure for CLSM mixes comprising alum sludge as replacement of recycled fine aggregate, OPC along with SCMs like pulverized fly ash (PFA), GGBS, incinerated sewage sludge ash (ISSA) and silica fume (SF) as binders. Initial and final stiffening time for penetration resistance of 0.5 and 3.5 MPa were examined, and the addition of alum sludge even at 12.5 % increased the final stiffening time by 54.4 % (19.3 hours -29.8 hours). Higher replacement levels further delayed the stiffening. This was attributed to high absorption of water by sludge, because of high clay content, delaying the stiffening and high organic matter in sludge (reflected by LOI of 21.6 %) also hampered portlandite formation and pH increase thereby slowing hydration. Similarly stiffening time was also examined using different SCMs, and doubling the binder content (OPC+PFA) from 20 to 40 % caused a reduction of 18.6 % in final setting time, but use of the other SCMs viz GGBS, ISSA and SF led to increased stiffening time. The rise in binder

(OPC+PFA) caused bundling of solid particles leading to densification of the mix structure and shortening of the setting duration. However, delayed setting by incorporation of other SCMs was resulted due to their increased water demand for the required flow leading to slow hydration. The factors such as more sheets of particles of GGBS, porosity of ISSA, high fineness with large surface area of SF particles, raised the water demand.

Do et al. (2019) investigated the setting time of the CLSM mixes prepared using fly ash (Fa), red mud (Rm), lime (L) and gypsum (G) as cementless binders as Fa-RmLG along with pond ash as fine aggregate. Varying factors were G/Rm, Fa/RmG, L/RmG for testing different properties of the mixes. It was observed that with an initial setting time of 24.5 hours for a G/Rm value of 0.40, setting time increased by 9.4 %- 27.3 % for increased gypsum in terms of G/Rm ratios between 0.75-6.0. Setting process is delayed due to the quick reaction of gypsum with calcium aluminates to form calcium sulfoaluminate hydrate that made a protective layer over the calcium aluminate and hampered the hydration. Increased fly ash content in terms of Fa/RmG from 1.29 to 1.71 caused a drop in the initial setting time from 39.1 to 28.9 hours which reduced to around 25 hours for Fa/RmG of 2.14 to 3. The initial setting time dropped drastically from 52 hours to 24.5 hours with increasing L/RmG ratio from 0.14 to 0.43 and further dropped slightly to 20 hours for L/RmG from 0.43 to 0.71. The quicker setting leading to short setting time was attributed to the rise in OH^- ions available from calcium hydroxide.

Qian et al. (2019) investigated the setting behavior of CLSM mixes using excess excavated soil as replacement of sand with cement and fly ash as other constituents. Penetration resistance of 0.50 MPa was the reference stiffness level. For a given sand/soil ratio of 0.43, increased cement content from 40 to 112 kg/m^3 caused the setting time to decrease from 870 minutes to 705 minutes. Similarly for the sand/soil ratio of 0.18 and 0, a rise in cement respectively from 37 to 101 kg/m^3 and 34 to 103 kg/m^3 decreased the setting time from 1035 to 825 minutes and from 1215 to 930 minutes respectively. The presence of cement led to an occurrence of hydration products forming a network structure and causing a loss of fluidity/plasticity of the mix. Since hydration product calcium hydroxide is known to strongly absorb soil particles, the increased setting time for lowered sand/soil ratio i.e., high soil content, was attributed to absorption of fine soil particles over the hydration products which hindered the hydration activity that delayed the setting process.

Fang et al. (2019) studied use of water works sludge as 0-20 % replacement of recycled fine aggregate in the CLSM along with OPC, incinerated sewage sludge ash (ISSA)/fly ash (FA) and accelerators as other constituents. The final setting time for the penetration resistance of 3.5 MPa was observed. Addition of 0-20% sludge resulted in a setting time of 2.4-55.7 hours with 4 % cement content and 2.0-58.0 hours with 6% OPC. The stiffening time increased due to the addition of sludge attributed to retardation of hardening of the mix due to high organic matter in the sludge. This was validated by TGA results also by presence of a distinctive peak of mass change at 410^{o} C representing decomposition of hydration product Ca $(OH)_2$.

Ho et al. (2022) studied the characteristics of CLSM comprising waste water treatment sludge (WTS) as 0-80 % (of the fly ash and OPC), NaOH based alkali accelerator (Na_2O in NaOH as 0, 3, 5 and 10 % of the sum of OPC, fly ash and WTS), fly ash, and OPC. It was reported that for the mixes with w/b of 0.65 and an accelerator factor A of 5 %, the initial setting time (IST) decreased initially for addition of WTS up to 20 %, constant for 20-40 % and increased at 40-80% value. Initial reduction of setting time was the result of finer WTS particles than fly ash and OPC, which caused higher absorption of water helping the hydration and faster setting. The increase of setting time between 40-80 % WTS addition was due to the reduction of OPC content resulting in diminished hydration activity and longer setting time. Hwang et al. (2017) also similarly observed a longer setting time for an addition of WTS in CLSM mixes with GGBFS and NaOH as other constituents, which was attributed to the reduction of GGBFS by increased WTS, since GGBFS was known to provide early strength and shortened setting time to the mix.

2.3.5 Loading suitability (Ball drop resistance)

A ball drop test as per ASTM D 6024 is conducted for examining the loading suitability of the CLSM. A standard ball is dropped over the surface of the CLSM and the diameter of the impression left over the surface is recorded. CLSM showing an impression diameter of 76 mm or less is considered suitable for loading.

Wang et al.(2013) has observed that the ball drop indentation diameter at 1-day old CLSM for rubber particle addition of 0-40 % as replacement of fine aggregate has been below 50mm for CLSRC and for CLSRLC below 64mm, which is less than 76mm that make them suitable for loading. The CLSRC group used normal coarse aggregate and CLSRLC used reservoir silt light-weight aggregate. A higher impression value for CLSRLC is attributable to the floatation of light weight aggregate due to its porous nature and delayed setting time. It was also observed that the drop weight impression reduced by average 1.2mm and 1mm for CLSRC and CLSRLC respectively with the incorporation of 10 % rubber particles. Reduced drop weight impression for the addition of rubber particles has been reported to exhibit an increased instant impact absorption resistance to dynamic loadings.

Achtemichuk et al.(2009) investigated the loading suitability with respect to ball drop tests on the CLSM having slag content added progressively as percent of dry mass of RCA. The loading suitability time for achieving 76mm diameter of ball impression recorded in respect of CLSM with fine RCA at 10 and 20 % slag content was 24 hours and 15 hours respectively. A lesser time of 8 hours and 5 hours was observed in respect of the CLSM with fine/coarse RCA with slag content of 5 and 10 % respectively. It has been seen that hardening time or time for loading suitability has reduced with increasing slag content in CLSM using both kinds of RCA. The slag, having cementing characteristics, is adding to the strength. It is also notable that with lower slag content less time has been observed for CLSM with fine/coarse RCA rather than only fine RCA. Shorter hardening time for CLSM having fine/coarse RCA is reported to be attributable to better packing of mixed constituents due to the addition of slag, reflected in higher unit weight.

Lachemi et al. (2008) in a study of CLSM, also examined the effect of CKD addition upon the ball drop setting time for achieving 76 mm indentation. Ball drop setting time of the four mixes designated as mix-1, mix-3, mix-8 and mix-10, with CKDs from four different sources, added at 4, 10, 15 and 30 % ranged between 15-25 hours, 18-43 hours, 52-122 hours and 48-116 hours respectively. Mix-1 and mix-3 had cement content also at 4 % and 2 % in addition to CKD. Increased ball drop setting time for mix-3 compared to mix-1 has been attributed to the reduction of cement content since cement undergoes fast hydration. Similarly mix-8 also had longer ball drop setting time than mix-3 and mix-1 possibly due to the reduction of cement to nil.

Kuo et al. (2013) studied the setting behavior with ball drop resistance test of CLSM containing waste oyster shells (WOS) as 0-20 % replacement of natural fine aggregate. The test was conducted at 1 day age to see if the indentation diameter was less than 76 mm or not. CLSM with indentation of 76 mm or less can be considered to have achieved sufficient bearing capacity to allow further construction. The indentation of the CLSM mixes was 49 to 59mm which was less than 76mm, meaning the mixes had gained the desired strength. With increased WOS addition above 5 % up to 20 % the indentation increased from 49 to 59 mm i.e., by 20 %, showing a delayed setting owed to high porosity of WOS as in the penetration resistance test.

Sheen et al. (2013) examined the ball drop values at 1-day age in a study of CLSM using surplus soil and GGBFS as constituents with the mixes prepared with three sand:soil ratio variations (6:4, 5:5 and 4:6) and the addition of slag as replacement of cement (0-30%). Comparison of the ball drop values was made with the indentation value of 76 mm. For three sand:soil ratio of 6:4, 5:5 and 4:6, with the addition of slag from 0-30%, the ball drop values increased from 84-98 mm (16.7 %); from 87-107 mm (23 %) and from 92-108 mm (17.4 %) respectively. While none of the mixes was suitable for loading after 1 day, since failing to comply 76 mm value, the ball drop values increased with addition of slag. This was attributed to the slow rate of hydration of slag compared to cement that delayed the loading suitability. Comparing the values for three sand soil ratios with no slag, the minimum ball drop value was for the highest sand content (6:4) mix, meaning thereby that addition of sand reduced the indentation or shortened setting time or the addition of soil delayed setting by obstructing the capillary water release for use in hydration.

Sheen et al. (2014b) also studied the setting behavior by the 1 day ball drop resistance of the CLSM with the addition of 0-30 % stainless steel reducing slag (SSRS) as replacement of OPC with varying w/b at 3.4, 3.6 and 3.8 forming three groups. The ball drop indentation increased from 78-103 mm, 89-105 mm and 106-128 mm upon addition of SSRS in mixes of three w/b respectively, which was attributed to content decreasing of OPC by SSRS addition and more water with higher w/b.

2.4 HARDENED STATE PROPERTIES

The hardened state properties of CLSM like unit weight, water absorption, unconfined compressive strength, California bearing ratio (CBR), drying shrinkage and permeability have been reported by different CLSM research studies and some of the same are discussed in the following sections.

2.4.1 Hardened state unit weight

Taha et al. (2007) investigated hardened unit weight at 28 days of the CLSM prepared with industrial by-products, namely cement by pass dust (CBPD), copper slag and incinerator ash all considered as cementitious materials, which replaced fly ash, an important constituent of the CLSM. Cement and sand were the other constituents used in the study. Two methods of curing i.e., in air and in sealed plastic bags, were examined. With unit weight of the mixes ranging between 1380-2140 kg/m^3, the mixes using cement and sand showed the maximum unit weights of 1940-2050 kg/m^3. The unit weight of the mixes with sand replaced by incinerator ash and cement by CBPD or copper slag were 1380-1410 kg/m^3. The lowered unit weight of CLSM with by-products were attributable to lower specific gravities such as that of incinerator ash as 2.58, CBPD as 2.4 compared to cement having a specific gravity of 3.15 and sand having 2.7. Also, copper slag, with the highest specific gravity of 3.45 and a sand CLSM mix, resulted in maximum unit weight of 2140 kg/m^3. Different materials with varying specific gravities affected the unit weights of the CLSMs.

Naganathan et al. (2012) studied the hardened unit weight of the CLSM prepared with constituents cement as binder, bottom ash (BA) and quarry dust (QD) as aggregates with varying BA/QD ratios and cement to total aggregate ratios (c/TA). The unit weight of CLSM mixes in the hardened state at 28 days ranged between 1414 kg/m^3 to 2123 kg/m^3. It has been observed that hardened unit weight is higher for mixes having higher QD i.e., aggregate combination BA/QD ratio of 0/100, and is lower for the CLSM having higher BA such as BA/QD of 100/0. It has been inferred that the addition of QD raises the hardened unit weight. Apparently, it is due to the higher specific gravity (2.59) of QD as compared to 1.83 of BA that might have raised the unit weight of the matrix.

Nataraja and Nalanda (2008) in a study of CLSM mixtures using industrial by products, such as RHA, QD and fly ash as aggregate, observed the hardened unit weight of the mixes. The dry unit weight of 899-1832 kg/m^3 and saturated surface dry unit weight 1365-2088 kg/m^3 were reported for different mixes. The values being more than 800 kg/m^3 were comparable with regular CLSMs as per ACI 229 (ACI 229R, 1999). Also, lesser dry unit weights in comparison to the saturated surface dry state are due to loss of moisture. The mixture having RHA had a lower density range of dry unit weight of 899-1340 kg/m^3 and saturated surface dry unit weight 1365-1612 kg/m^3 in comparison to 1328-1832 kg/m^3 and 1598-2088 kg/m^3 for rest of the by-products, attributable to the lower specific gravity (2.04) of RHA than other products (QD=2.63, Sand=2.68). The mixtures with QD had higher density than with sand possibly due to QD (FM=2.03) being finer than sand (FM=2.54) leading to better packing of the matrix. The study concluded that the unit weight is mainly related to the specific gravities and fineness of the constituent used as filler or aggregate.

Lee et al.(2013) studied the cementless CLSM mixes using fly ash and slag as binders and bottom ash as fine aggregate along with solid NaOH as alkali activator for binders. It was reported that the unit weight increased from 1625 to 1710 and 1730 kg/m^3 for changing the slag content from 10 % to 20 % to 30 % of the binder content. The higher density at 2900 kg/m^3 of the slag than 2380 kg/m^3 of fly ash was cited as the reason for the above change in unit weight. Increased bottom ash/ binder ratio from 1.5 to 2.5 reduced the unit weight from 1645 to 1615 kg/m^3 probably due to its lesser specific gravity of 1.87 than both fly ash and slag.

2.4.2 Water absorption

Katz and Kovler (2004) studied the water absorption of the CLSM mixes having industrial by-products such as fine wastes i.e., cement kiln dust (CKD), asphalt dust (AD) and coal fly ash (FA) and coarser wastes i.e., coal bottom ash (BA) and quarry waste (QW). The mixes with CS as coarse waste and 500 kg/m^3 of fine wastes resulted in an absorption of around 15 %. The mixes with coarse wastes BA/QW with 500 kg/m^3 fine waste, as well as CS with 1000 kg/m^3 of fine wastes, resulted into around 25 % absorption. The highest absorption was for CKD mixes. The higher absorption was linked to higher water demand of the mix, as increased fineness of the mix due to the presence or addition of wastes (finer FA/AD/CKD and QW fines) and porosity of BA raised the water demand of the mixes.

Nataraja and Nalanda (2008) investigated water absorption of hardened CLSM mixtures made using RHA, QD and Fly ash as constituents. The study reported that 28 day cured CLSM specimen showed 30 minutes absorption between 11 to 51% that remained almost the same even after 24 hrs. Thus, it indicated that CLSMs so prepared absorbed the maximum water initially in the minimum time. RHA mixtures, due to its high porosity, showed largest absorption compared to that of mixes with other materials. The absorption values for cement-fly ash mixtures at ratios 1:17.5 to 1:10 to 1:5 showed a reduction from 27.5 % to 22.5 % and for RHA mixtures at the same ratios showed a reduction from 55 % to 42 % in 24 hours. For the richer mixes, the reduction of the by-product relatively increased the cement content. Thus, it was concluded that absorption also reduced with increasing cement content.

W.-T. Kuo et al. (2013) studied the absorption of the 28 day CLSM mixes by adding waste oyster shells (WOS) sand as a 0-20 % replacement of natural fine aggregate. The absorption increased between 12.1 to 14.0 % compared to the value of 12.4 % for 0 % WOS sand. The absorption dropped initially to 12.1 % for 5 % WOS addition, but increased at more than 5 % WOS addition. Decreased absorption initially was attributed to filling of pores by CSH gel formed due to the pozzolanic reaction of fly ash. However, increased absorption at higher WOS levels was attributed to higher porosity of the WOS reflected in an absorption rate of 7.7 % against 2.2 % for fine aggregate.

2.4.3 Compressive strength

Katz and Kovler (2004) studied the 28 day compressive strength of CLSM mixes having industrial by-products such as fine wastes i.e., cement kiln dust (CKD), asphalt dust (AD) and coal fly ash (FA) and coarser wastes i.e., coal bottom ash (BA) and quarry waste (QW). Mixes with 50 kg/m^3 cement and 500 kg/m^3 of fine waste showed compressive strengths of 3.4, 0.3 and 2.2 MPa for FA, AD and CKD respectively as fine waste. Mixes with 50 kg/m^3 cement and 1000 kg/m^3 of fine waste showed compressive strengths of 2.3, 0.15 and 1.5 MPa and mixes with 100 kg/m^3 cement and 500 kg/m^3 of fine waste showed compressive strengths of 7.2, 1.2 and 4.6 MPa. Among all the fine wastes, the CLSM mixes with FA showed the maximum compressive strength which was attributed to the pozzolanic activity of FA. The residual cementing property of CKD was responsible for the higher strength of CLSM mixes using CKD in comparison to inertness of AD reflected by the lowest strength of the AD mixes. The reduced strength for use of double the fine wastes was attributable to more water demand in the mix for a rise in fineness. Doubling the cement content showed an increase of around 300% in AD mixes compared to 100% in FA/CKD mixes, which was attributable to the inertness of AD and the dominant effect of cement on strength, unlike in the case of pozzolanic/cementing nature of FA/CKD where fine waste and cement jointly contributed to the strength. The higher strength for replacement of CS with BA rather than QW, was attributed to the higher pozzolanicity of BA. Observations of higher long-term strength at (90 days) in FA/CKD/BA mixes validated the contribution of pozzolanic/cementing activity of these materials whereas the strength remaining unchanged after 7 days validated the inertness of AD.

Taha et al. (2007) studied the compressive strength of CLSMs having varying quantities of by-products, cement by pass dust (CBPD), copper slag and incinerator ash with cement and sand as other constituents. Two material groupings comprising varying contents of cement, sand, incinerator ash, and CBPD, designated as A and B (1 to 5) with curing in air and in sealed plastic bags respectively were experimented. Group C (1 to 3) with cement, sand, ash and CBPD with cylindrical specimen and group D (1 and 2) with cement, sand, ash and copper slag were also examined. The 28 days compressive strength results for different mixes having cement as the primary binder were the highest in each group i.e., mix, A1-0.432 MPa, B1-0.429 MPa, C1-0.850 MPa and D1-0.300 MPa. Incinerator ash, CBPD and copper slag replacing cement showed minimum strength around 0.135/0.100/0.418/0.079 MPa in group A/B/C/D. Therefore, these by-products were termed as non-pozzolanic materials when used alone and cement was required in addition to activate the waste materials for getting better results. Some mixes which were cured in air also showed reduced compressive strength at 56 days but those cured in plastic bags showed no such behavior.

Wang et al. (2013) in a study of rubber particles as a constituent of CLSM reported that the compressive strength at 1 day decreased with increasing rubber particles in CLSM as replacement of fine aggregate for both CLSRC and CLSRLC groups having normal coarse aggregate and the reservoir silt light weight aggregate respectively. For CLSRC, strength reduced by 0.30 MPa at 20% rubber particles incorporation compared to the control mix with normal fine aggregate. In the case of CLSRLC, strength reduced by 0.10 MPa for 10 % rubber particles and further reduced at higher replacement level. However, for more than 30% rubber particles, no significant change in compressive strength took place which is said to be a reflection of a reduced strength due to CLSM entering into an aggregate-particle separation stage. Also, reduced strength possibly can be attributed to replacement of strong natural fine aggregate with more flexible rubber particles.

Achtemichuk et al. (2009) investigated CLSM using slag and RCA in fine and fine/coarse grading, with the varying addition of slag as a percentage of dry mass of RCA. It has been reported that the 28 day unconfined compressive strength of CLSM with fine RCA using 5-10 % slag was below 2.1 MPa which is the prescribed level for future excavatability. The strength with 20-30 % slag has been reported as 7.2 and 5.8 MPa i.e., higher than 2.1 MPa that make it appropriate for structural fill and road base purposes. An observation of strength reduction for the slag content between 20 % and 30 % has been attributed to lower densification of the mix at 30 % slag level owing to increased cohesiveness due to increased fine content. Lower densification is reflected in the lower unit weight of 1986 kg/m^3 of 30 % slag mix against 2014 kg/m^3 of 20 % slag mix. CLSM with fine/coarse RCA has shown 28 day unconfined compressive strength 6.4 MPa and 7.8 MPa for 10 % and 20 % slag addition respectively. The higher strength of CLSM having fine/coarse RCA is reported to be attributable to a better packing of mixed constituents due to the addition of slag reflected by higher unit weight. Results of the research showed that CLSM could be prepared only by using by-products without using the conventional binder cement and the pozzolanic reactions can take place between the alkali available in residual paste of RCA and slag leading to strength gain. However, use and quantity of any SCM in a CLSM may be decided on case-to-case basis based upon the effect upon compressive strength that may impact future excavatability.

Naganathan et al. (2012) investigated compressive strength of various mixes of CLSM with constituents, cement as binder, BA and QD both combined as aggregate taken in different proportions. The cement to total aggregate c/TA in eight levels (0.40 to 0.05) at a difference of 0.05 and each having BA/QD in five levels (100/00 to 00/100) with 25 % gap. The 28 days compressive strength of the mixes, tested upon 70.7 mm cubes, ranged between 0.22 MPa to 11.4 MPa. Considering cylinder strength to be 0.80 times the cube strength, the 28 days cylinder strength range worked out to 0.18 MPa to 9.1 MPa, the maximum value being very near to required 8.3 MPa as per ACI 229R for CLSMs which made them suitable for different CLSM applications. The study of the effect of w/c upon compressive strength showed an exponential relation depicting a reduction of strength with an increased w/c. This is attributable to the existence of extra water above hydration requirements, which causes internal voids due to water pockets in the transition-zone between the aggregate and cement paste in a matrix, and result in weakening of the bond among the matrix constituents. Considered as an important determinant for the strength, the weakened bond caused lower strength. The strength increased with increasing QD in aggregate combination which has been attributed to the high amount of silica present in QD producing more C-S-H gel during hydration.

Her-yung (2009) in a study of CLSM having three w/b ratio (1.1, 1.3, 1.5) levels with further four levels (0, 10, 20, 30 %) of glass-sand addition as normal sand replacement, reported that the 91 day compressive strength of the mixes reduced by 4-10 % across different mixes when waste glass-sand level is increased to 30 %. This has been attributed to lesser effective binding of cement and glass-sand particles as compared to normal sand particles. While noting that the strength is highest for the control mix, the 91 day compressive strength values around 4.8 MPa, 3.8 MPa and 2.8 MPa also decreased with increasing w/b ratios of 1.1, 1.3 and 1.5. The higher w/b ratios (greater than 1) mean more water and less cement exists in the CLSMs which is responsible for this reduction. Notably the compressive strength of CLSM at 10 % glass-sand addition has been almost equivalent to the control mix with normal sand as aggregate.

Lachemi et al. (2008) in a study of CLSM, examined the effect of CKD addition upon the compressive strength. The mixes designated as mix-1, mix-3, mix-8 and mix-10, with CKDs from four different sources, added at 4, 10, 15 and 30 % were checked. Mix-1 also had cement at 4 % and mix-3 had 2 % cement. 28 days compressive strength of CLSM mixes ranged between 1.2-2.2 MPa, 1.9-2.6 MPa, 0.7-1.9 MPa and 2.0-2.7 MPa for mix-1, mix-3, mix-8 and mix-10 respectively for different CKDs. Correspondingly, 7 days strength ranges were 0.7-1.5 MPa, 0.7-1.3 MPa, 0.2-0.7 MPa and 0.8-1.0 MPa. The strength gained with age and considering 7 days strength as percentage of 28 days strength, mix-1 gained the highest around 62-72 % of the 28 days strength and this faster strength gain was attributed to presence of cement along with CKD. In only CKD mixes this rate was less at around 35 %. It was concluded that increased CKD content resulted in increased strength as CKD was also considered as a cementitious material along with cement.

Lachemi et al. (2010) studied the effect of varying the contents of CKD and blast furnace slag in the CLSM mixes upon their compressive strength. CKD and slag were considered as binders and other conventional materials such as fine aggregate and water were also used. The 28-day compressive strengths of CLSM mixes without slag but with 200 kg/m^3 and 300 kg/m^3 of CKD i.e., Mix-1 and Mix-8 were 2.6 MPa and 1.5 MPa respectively, where mix-1 also had a cement content of 40 kg/m^3. Considering the lowered strength at 1.5 MPa of mix-8, even with a higher CKD content at 300 kg/m^3 led to the conclusion that CKD was having very low reactivity and any strength gain beyond 28 days was not expected. Further for the mixes with constant CKD content of 200 kg/m^3, increasing the slag content from 40 to 300 kg/m^3 enhanced the 28 days strength from 1.93 to 8.11 MPa. Similarly in case of mixes with CKD at 300 kg/m^3, increasing the slag content from 20-45 kg/m^3 also caused a rise of strength from 1.72 to 2.11 MPa. Keeping in view a strength gain of 227 to 781 % between 7 and 28 days of the slag mixtures, further strength gain was expected. All this was attributed to the pozzolanic nature of slag.

Naik and Singh (1997a) investigated compressive strength of flowable slurries made using clean sand (FS1) and used foundry sand (FS2) as partial replacement of two types of Class-F fly ashes (F1 and F2) along with cement. Foundry sands replaced fly ash by 30, 50, 70 and 85 % in two sets of mixes i.e., one set for each fly ash F1 and F2. 28 days compressive strength of flowable slurries by varying FS1 and FS2 while using F1 fly ash ranged between 0.28-0.55 MPa and for F2 fly ash between 0.34-0.62 MPa. Reduced water content or lower flow in F2 mixes was the reason attributed for higher strength. 91 day strength were between 0.31-0.76 MPa for F1 and 0.38-0.76 MPa for F2 fly ash. Higher strength levels at 91 day led to the conclusion that strength increased with age. Strength also increased with increase in foundry sand content up to certain level and decreased thereafter. The optimum level to achieve maximum compressive strength for clean sand FS1, was 30 % for F1 and 70 % for F2 fly ash mixes and in the case of used foundry sand FS2, it was 30% for both F1 and F2 fly ash type. The reason for the observed higher replacement level for clean sand (FS1) in F2 mixtures is possibly due to higher 28 days strength activity index (87) of F2 fly ash compared to (75) of F1 and lower replacement level for used foundry sand (FS2) is attributed to its possible lower quality in comparison to FS1. It also reported that replacement of fly ash up to 85% by foundry sand can be used in making excavatable CLSM suitable for many applications.

Nataraja and Nalanda (2008) in study of CLSM mixtures using industrial by products such as RHA, QD and fly ash as aggregate examined the 7 days, 28 days and 60 days compressive strengths of the different mixes. 13 CLSM mixes having constituents' ratios of cement-fly ash-sand (CFS) and cement-RHA-sand (CRS) as 1:12:50, cement-sand (CS1 and CS2) as 1:25/12.5, cement-QD (CQ1 and CQ2) as 1:12.5, cement-fly ash-QD (CFQ) and cement-RHA-QD (CRQ) as 1:12:50, cement-fly ash (CF1, CF2 and CF3) as 1:17.5/10/5 and cement-RHA (CR1, CR2 and CR3) as 1:17.5/10/5 were tested. The compressive strength by cube test of all the mixes at 7 days, 28 days and 60 days ranged between 0.044-4.011 MPa, 0.063-4.233 MPa and 0.077-4.316 MPa respectively. Only a marginal enhancement in compressive strength beyond 28 days was observed. Therefore, enhancement of strength with age was evident but the marginal change beyond 28 days was attributed to a reduction of pozzolanic activity of the cementitious material. The observed range of the compressive strength for different CLSM mixes being very large meant that the quantity of materials, including water, has influenced the strength. 28 day strengths of fly ash mixes (CF1, CF2 and CF3) ranging between 0.617-4.233 MPa were highest among all the mixes which was reported to be because of the pozzolanic activity of the material.

Zhen et al. (2013) explored the use of industrial by-products namely dewatered sludge (DS) and municipal solid waste incineration (MSWI) bottom ash as constituents for development of controlled low strength material. Calcium sulfoaluminate cement (CSA) was also used as binder. In the DS: MSWI: CSA proportions, the combined MSWI and CSA were kept equal to DS by weight, and further there were three mixture ratios between the two as 1/9, 4/6 and 8/2. The reference mix was without MSWI. The as-received less than 40 mm MSWI ash was subjected to oven drying at 65 degree C, crushed to less than 20 mm size, further milled to a size less than 4 mm. Additionally, the MSWI bottom ash was given a thermal treatment involving firing milled MSWI ash at 900 degree C for 1hour. Compressive strength results for mixes with oven dried and milled MSWI ranged between 2-6.2 MPa and with thermally treated MSWI ash between 0.7-4.6 MPa against the 2.5 MPa registered for the reference mix. The reduction of strength after the thermal treatment of the MSWI showed that thermal treatment did not help and was not required. This was for the reason that highly denser surface of MSWI ash caused by thermal treatment blocked transportation of water and ions required for hydration. The strength of mixes with oven dried and milled MSWI for DS: MSWI: CSA ratios of 1:0.1:0.9, 1:0.4:0.6 and 1:0.8:0.2 (mix I_{65}, II_{65} and III_{65}) at 6.2 MPa, 3.5 MPa and 2.0 MPa respectively and for thermally treated MSWI (mix I_{900}, II_{900} and III_{900}) at 4.6 MPa, 2.5 MPa and 0.7 MPa showed that the addition of MSWI caused a reduction of strength. This was attributed to excess metal gels and organic matter in the MSWI retarding the hydration of cement. The optimum milled MSWI was at 40 % in MSWI/CSA mixture (mix II_{65}) as at 80 % level (mix III_{65}) the strength was lower (2.0 MPa < 2.5 MPa) than the reference mix.

Kuo et al. (2013) studied the behavior of the compressive strength parameter of the CLSM containing waste oyster shells (WOS) added as 0-20 % replacement of natural fine aggregate. The compressive strength tests were conducted at 1, 7, 28, 56 and 91 days of curing. Compressive strength of the mixes at 1 day curing age was between 0.96 to 1.67 MPa and at 28 days was between 4.21 to 6.63 MPa and after 28 days, very little strength gain was observed. Also, the strength at 5 % WOS replacement level was more than at 0 % level which was attributed to the possibility of filling of the pores up to this level. However, at a higher level of WOS above 5 %, the pore filling possibility goes and the resulting increased porosity and more absorption caused a reduction of strength. Increased WOS being finer also increased fineness and reduced the FM of the fine aggregate which also was related to reduced strength.

Sheen et al. (2013) studied the compressive strength of CLSM mixes using surplus soil, GGBFS as constituents with three sand:soil ratio variations (6:4, 5:5 and 4:6) and addition of slag as replacement of cement (0-30%). 28 days compressive strength for the mixes with sand soil ratios 6:4, 5:5 and 4:6 and addition of slag as 0-30% ranged between 0.84-0.59 MPa, 0.73-0.59 MPa and 0.61-0.41 MPa respectively. 91 days strength ranged between 0.90-0.65 MPa, 0.80-0.63 MPa, 0.64-0.45 MPa. Continued hydration of cementing materials was responsible for improved strength at 91 days. The relative strength ratio (at 91 days) was the ratio of strength with slag at different levels and without slag (control) and it was less than 1 in each sand:soil ratio mixes, meaning the addition of slag reduced strength. The low CaO/SiO_2 ratio of slag compared to OPC increased the water/cement ratio (w/c) due to reduction of cement with a fixed water-binder, were attributed with the reduction of strength. The decrease of strength around 27.4-30.5 % with increasing soil content in sand:soil ratios from 6:4 to 4:6 also was attributed to the fact that for a fixed w/b mix with higher soil-content resulted in more workability and lower strength.

Sheen et al. (2014b) also studied the effect of addition of 0-30 % stainless steel reducing slag (SSRS) as a replacement of OPC upon the compressive strength of the CLSM mixes, and using three w/b ratios of 3.4, 3.6 and 3.8. The 28 days and 56 days compressive strength ranged between 0.81-0.42 MPa and 0.57-0.88 MPa for all the tested mixes, showing increased strength with age attributed to continued hydration of cementitious matter. Also, the 28 days compressive strength decreased by 27 %, 18 % and 33 % upon addition of 30 % SSRS in mixes of three w/b respectively, which was attributed to SSRS contributing less to strength than OPC. The 28 days strength without slag for three w/b was 0.81 MPa, 0.71 MPa and 0.61 MPa and the lowering strength at higher w/b ratios was a result of formation of high pore volume by more water.

Sheen et al. (2014a) studied compressive strength of CLSM comprising varying fly ash (FA) content as 0-45 % replacement of OPC in 3 groups of mixes with binder content (PC+FA) at 80 kg/m^3, 100 kg/m^3 and 130 kg/m^3. The compressive strength reduced with the addition of FA (0-45%) from 0.47-0.21 MPa (55.3%), from 0.69-0.21 MPa (70 %), from 1.2-0.74 MPa (39 %) respectively in the three binder groups. Comparison of results showed a lowered compressive strength by addition of FA which was attributed to FA being not as good as OPC.

Lee et al. (2013) in the studied compressive strength of the cementless CLSM mixes using fly ash and slag as binders and bottom ash as fine aggregate along with solid NaOH as alkali activator for binders. Enhancement in 28 days compressive strength of the mixes at 1.16 MPa, 7.09 MPa and 15.08 MPa with rising slag content of 10 %, 20 % and 30 % of the binder content in the mixes was attributed to the fact that more slag led to a higher hydration degree resulting in more CSH gel that made the mix denser to give more strength. Rising 28 days compressive strength results of 1.11 MPa, 2.03 MPa, 6.27 MPa and 7.72 MPa for increasing NaOH content of 1.5 %, 2.5 %, 3.5 % and 4.5 % of the binder was attributed to higher molarity of the alkali solution, hydrolyzation of more OH ions on slag, fly ash, dissolution of Si, Ca and Al from slag to form CSH gel by polymerization. Reducing compressive strength from 7.72 MPa, 1.5 MPa, to 0.42 MPa against bottom ash/binder ratios of 1.5, 2.5 and 3.5 was attributed to the non-homogeneity and higher demand of water due to higher bottom ash in the mix. A lesser strength at 91 days than 28 days was observed which was attributed to the evolution of cracking inside the mix due to drying shrinkage.

Park et al. (2017) investigated the compressive strength development up to 56 days of the CLSMs due to the variation of slag, CBFC bottom ash (as aggregate), water and NaOH (alkali activator). Compressive strength increased slightly by an addition of 2-4 % NaOH with not much difference at 6 %. Due to the low NaOH molarity in the CLSM at less than 1, the content of NaOH at 2-6 % level was insufficient to result in distinct compressive strength results. Further, distinct lowering of compressive strength at all ages with higher water content was also attributed to the decreasing molarity of NaOH. With NaOH content fixed the addition of water resulted in lower molarity as reported (Lee et al., 2013). The addition of aggregate CFBC bottom ash from 1.5 to 2.0 times the binder level caused a higher strength at all ages but at 2.5 times level the compressive strength at 28 days was lower than at 2.0 times level which however became a maximum at a later age (56 days). The higher calcium level in CFBC bottom ash getting released owing to alkali activation followed by its participation in hydration led to higher strength. Strength gain at the later age was result of low reactivity of the reactive component in the bottom ash than in the binder material. Also, the less reactive calcium-source in CFBC ashes were responsible for the slow strength gain at early ages and of continued strength gain even after 28 days, reflected by higher strength at 56 days. The compressive strength enhanced from 0.33 to 0.98 MPa, 1.69 to 3.65 MPa and 2.22 to 4.75 MPa respectively at 7 days, 28 days and 56 days by increasing slag content from 0-0.3 in the CLSM. The strength was proportional to the NaOH molarity of CLSM which established the fact that alkali-activation of the calcium source was an effective mechanism of strength gain.

Wang et al. (2018) studied the CLSM mixes comprising alum sludge as replacement of recycled fine aggregate, OPC along with SCMs like pulverized fly ash (PFA), GGBS, incinerated sewage sludge ash (ISSA) and silica fume (SF) as binders. Addition of sludge by even 12.5 % caused a 75 % reduction of the 28 days compressive strength attributed to high water absorption and inorganic matter of the sludge interfering in the hydration by hampering CH creation and pH rise. The higher sludge levels above 12.5 % caused high absorption and even crumbling of hardened CLSM when immersed in water. Doubling the binder (PFA+OPC) increased the compressive strength attributed to lowered water demand due to spherical particles of PFA but use of other SCMs delayed the setting time owing to their higher water demand. Water demand was considered as an important controlling factor.

Alizadeh (2019) investigated the compressive strength of the CLSM mixes comprising cement, fly ash, sand and water. It was reported that the paste volumetric ratio i.e., volume of paste (cement + SCM + water) to total mix volume PVR if increased in the mix caused a rise in compressive strength initially to PVR of 0.40 but caused a reduction of the strength at higher PVR. This was attributed to the fact that PVR=0.40 was 1.2 times of the void ratio of aggregate which was near the optimum ratio of paste to voids (1.5-2.0) for maximum strength. The reduced strength at higher PVR was attributed to incomplete pozzolanic action by not all cementitious matter taking part and the reduced crack tortuosity. Crack tortuosity is the path that a crack follows from one face of the specimen to other at failure. Increased PVR led to reduction of aggregate in the mix which would reduce crack tortuosity. Increased Portland cement to cementitious materials ratio as (pc/cm) caused enhanced strength due to the higher hydration potential of cement. The lower water to cementitious material (w/cm) ratio showed higher strength on expected lines as the higher water content would increase the capillary porosity leading to lower strength.

Zhang et al. (2018) studied the effect of water to solids ratio (W/S), accelerator to biner ratio (A/B) and binder to recycled fine aggregate ratio (B/R) upon the compressive strength of CLSMs. OPC, sulfoaluminate cement clinker-based accelerator, recycled fine aggregate from construction and demolition waste, fly ash were the constituents. Early hour strengths for 1-4 hours were monitored, and for A/B ratio 20-40 % the strength of 0.41 to 0.79 MPa dropped to 0.13 MPa for A/B at 50 %. Heavy production of ettringite and alumina-gel by calcium sulfoaluminate in the accelerator caused quick hydration, which covered the cement particles resulting in inhibition of the hydration progress and thus reduced strength. Increase of W/S led to more free water being not conducive for strength development resulted into reduction of strength. Compared with the reference B/R at 0.13, reduced cementing material and the resulting hydration products were the reason for the lower compressive strength at a B/R of 0.07-0.10. But reduced strength at a higher B/R of 0.15 than 0.13 was attributed to the relatively reduced fine aggregates resulting in lesser absorption of water causing more free water in the mix. The development of long-term strength (up to 91 days) showed A/B ratio up to 20 % did not impact the strengths. Strength at A/B of 30-40 % were higher than the control but at A/B of 50 % strength was lower than the control and remained unchanged after 28 days. Lack of SiO_2 caused by high accelerator proportion in the cementing material resulted into lower strength gain after 28 days. Increased W/S ratio from 0.27 to 0.30 caused a reduction of 91 days strength from 7.42 MPa to 4.89 MPa. Increasing B/R ratio from 0.07 to 0.15 caused a rise of around 400 % in 91 days strength due to the high binder content.

Mneina et al. (2018) investigated the compressive strength characteristics of the CLSM mixes using TOSW as 5-15 % replacement of fine aggregate with cement and fly ash as other constituents. Control mixes had no TOSW but having 30, 60 and 90 kg/m^3 cement content showed increasing 28 day unconfined compressive strength as 0.595, 1.436 and 4.771 MPa respectively, which was attributed to the increased pozzolanic activity by enhanced cement content with fly ash that was considered non-cementitious. Mixes with 60 kg/m^3 cement and with addition of 5-15 % TOSW, known to be inert, showed higher compressive strength range of 2.894-3.172 MPa than the 1.436 MPa of control mix and mixes with 90 kg/m^3 cement showed 4.364-6.848 MPa against 4.771 MPa of control mix. The dropping water/powder ratio with increasing TOSW was attributed to this rise in strength, since addition of TOSW reduced the water demand for a desired flowability of the mix and caused a reduction of water/powder ratio. The mixes with TOSW replacing both aggregate and fly ash showed unconfined compressive strength ranging between 0.298-0.423 MPa and 0.972-1.233 MPa for 60 and 90 kg/m^3 mixes which was quite a bit lower than the values of 1.436 MPa and 4.771 MPa of the control mixes. The reduction was attributed to reduced bonding between constituents due to dropped pozzolanic action in the absence of fly ash.

Kim et al. (2018) in a study of CLSM using mine tailings, cement as binders with varying incorporation of pond ash and natural sand as fine aggregate, reported that the 91 days compressive strengths of the mixes cured at 30^o C were higher than that at 5^o C. Further, the 91 days strength of mixes with pond ash (P1 and P2) cured at 5^o C, increased from 0.30 to 0.70 MPa (130 %) compared with mixes with sand (S1 and S2), and respectively from 0.50 to 1.70-2.40 MPa (200-300 %) when cured at 30^o C. Heightened pozzolanic activity of pond ash, which was strongly affected by temperature, was the reason for higher increase in strength.

Do et al. (2019) studied CLSM mixes prepared using fly ash (Fa), red mud (Rm), lime (L) and gypsum (G) as a cementless binder as Fa-RmLG, along with pond ash as fine aggregate. Varying factors were G/Rm, Fa/RmG, L/RmG and compressive strength was examined. At low level of gypsum G or high level of red mud Rm, quite higher early age (3 and 7 days) unconfined compressive strength (1.202 and 1.812 MPa) were observed for G/Rm ratio of 0.4. Mixes with high G/Rm ratio of 6, the 3 and 7 day tests showed reduced strength of 0.173 and 0.744 MPa. Red mud made the mix environment highly alkaline by providing OH^- ions on mixing with water, due to the availability of Al_2O_3, Na_2O and CaO in red mud, that resulted in faster hydration. On the other hand, higher gypsum content mixes showed higher later age strength which was attributed to gypsum providing more sulfate ions that reacted with alumina oxide from fly ash and calcium oxide from lime to form ettringites giving strength. For increased Fa/RmG in the mixes (1.29 to 2.14), the strength increased but the enhancement in compressive strength was much less but later age strength (28 days) increased substantially around 35 - 40 % over control (2.14) for Fa/RmG ratios of 2.57 and 3. In case of increase in lime content as (L/RmG) ratio, the strength increased for all ages of curing. It was also observed that at higher lime contents L/RmG of 0.57 and 0.71 the 28 days compressive strength rose substantially over the 7 days strength compared to lower rise in low lime i.e., L/RmG ratio of 0.14, 0.18 mixes. Release of OH ions, by lime in water, hydrolyzing the fly ash and pond ash surface leading to hydration of these pozzolanic materials and formation of CSH gel resulted in improvement in strength.

Qian et al. (2019) reported the reduction of compressive strength of CLSM mixes by using excess excavated soil as replacement of sand. The compressive strength for mixes with 5-15 % cement content and sand/soil ratio 0.43 was ranging between 0.54-1.18 MPa which reduced to 0.27-0.64 MPa for sand/soil ratio of 0. The reduction of strength due to lower sand/soil ratio i.e., lowered sand content due to addition of soil was owed to two reasons i.e., first one is soil covering the surface of sand that reduced bond force between cement and sand second is the soil particles getting absorbed upon hydration products that diminished further hydration resulting into low strength. Rise in cement content for all sand/soil ratios increased the strength.

Ho et al. (2022) studied the compressive strength of the CLSM mixes comprising waste water treatment sludge (WTS) as 0-80 % (of the fly ash and OPC), NaOH based alkali accelerator (A as Na_2O in NaOH as 0, 3, 5 and 10 % of sum of OPC, fly ash and WTS), fly ash, and OPC. Comparison of the 1-day compressive strength (mixes with A at 5 %) revealed that for an increase of w/b from 0.5 to 0.8, around 80 %, 79 %, 67 % reduction in compressive strength for WTS levels of 0 %, 20 %, 40 % was seen but almost no change at 80 % level. Increased w/b diluted the accelerator solution and reduction of accelerator concentration slowed the polymerization reaction for strength gain. Higher w/b also raised porosity leading to lowered strength of the mix. Increasing the A at 0, 3 and 5 % for the mixes having w/b at 0.50 and WTS at 0 %, the 28 days compressive strength was 5.88, 6.86, and 4.04 MPa respectively, whereas for higher WTS i.e., 20, 40 and 80%, the strength ranged between 2.17-0.19, 5.62-2.0 and 6.02-1.13 MPa. Negligible effect of A content on compressive strength at 0 % WTS level was seen. However, a higher impact at higher level of WTS was seen. This was attributed to accelerator activating the fly ash and WTS that facilitated their reaction with hydration products resulting into higher strength. With a given level of activator A, for the mixes having w/b 0.50 and for addition of WTS at 20 and 40 %, the compressive strength was higher by 40 and 31.7 % than that at 0 % WTS, with w/b 0.65 higher by 25.6 and 48.4 %, and with w/b 0.8 higher by 67.4 and 56.8 %. Compressive strength at 80 % WTS level was lesser than at that 0 % WTS level in all cases. Greater amount of active silica contributed by WTS, improved pozzolanic reaction with cement hydration products and filling effect due to finer WTS particles decreasing porosity caused higher strength up to 40 % WTS level. However, reduction of strength at 80 % WTS level was attributed to a reduced cement content in the mix.

2.4.4 California bearing ratio (CBR)

CBR is a measure for allowable bearing pressure or support of a sub-grade layer. A plunger of 50 mm diameter is penetrated into the material to be tested cast in a standard CBR mould. CBR value is determined taking the higher of the ratio of resisting load at 2.54 mm and 5.08 mm penetrations with corresponding standard load values.

Naganathan et al. (2012) investigated CLSM using cement as binder, BA and QD mixed as aggregate. CBR values for different CLSMs ranged between 5 and 59. The study of the relation of w/c with CBR value revealed that CBR decreases with increase in w/c. This could be a direct consequence of the reduced strength related to an increased w/c. Notably, observed values of CBR can be positively related with compressive strength since both the parameters reflect strength of the sub-grade. Also, observed CBR values were higher in mix with BA/QD as 00/100 i.e., higher QD component, which has been attributed to QD being heavier and denser than BA. It has been considered that in terms of types of soil, CBR range of 10–25 matches level of well compacted sand and 25-50 of very well compacted sand while in terms of sub-grade CBR of 8–30% equates fair to excellent sub-grade and 30-60% equates a good sub-base. Thus, mixes were considered good enough for sub-base and sub-grade applications like embankment filling, pipeline base etc.

Lachemi et al. (2008) in the study of CLSM, examined the CBR value of the mixes designated as mix-1, mix-8 and mix-10, with CKDs from four different sources, added at 4, 15 and 30 %. CBR values at ball drop setting time ranged between 30-50 %, 20-38 % and 23-45 % for mix-1, mix-8 and mix-10. Comparison of the results for mix-8 and mix-10 showed that addition of CKD in the mix increased the CBR value. Similarly higher CBR for mix-1 indicated that cement in the mix also increased CBR. CLSM mixes in the study with determined CBR values ranging between 20-50 % were considered equivalent to sand/gravelly sand/silty sand with standard CBR values between 20-50% as suggested by Bergeson et al. (1998).

2.4.5 Drying shrinkage

Nataraja and Nalanda, (2008) investigated drying shrinkage of hardened CLSM mixtures made using RHA, QD and Fly ash as constituents. Volume change was measured after 24 hours of mixing of water during setting of the specimen. The change in length was worked out by adding the change in bottom of bar by measuring with calipers and the crack width at top of the specimen. The study has reported that the RHA mixtures showed almost double the change undergone by fly ash mixtures. This was attributed to drying of water from the bulk of the RHA CLSM mixes instead of from the surface. Mixtures with higher cement content have also been shown to exhibit lower shrinkage and cracking. Further lower w/c requirement (w/c=2.3-7) for the desired flowability of 200 mm and lesser shrinkage (0.55 to 0.90 %) were observed for fly ash mixture as compared to w/c= 6-19 and shrinkage (1.62 to 2.75 %) of the RHA. It is notable to mention that the research paper has also mentioned w/cm i.e., water to cementitious material ratio, by considering fly ash and RHA as binding materials. The w/cm ratio for fly ash mixes is 0.4 and for RHA mixes was 1.0. A linear relationship has been reported between w/c and shrinkage for fly ash and the RHA mixes which means that as the w/c ratio increases the shrinkage will increase.

Katz and Kovler (2004) in a study of CLSM mixes evaluated the effect of varying the constituents upon drying shrinkage. Industrial by-products such as fine wastes i.e., cement kiln dust (CKD), asphalt dust (AD) and coal fly ash (FA) were varied from 500 to 1000 kg/m^3 and coarser wastes i.e., coal bottom ash (BA) and quarry waste (QW) were used to replace crushed sand. Result of early age shrinkage of base mixes at 24 hours were reflected by few fine cracks in AD and FA mixes but wider cracks in CKD mixes. Further at double the fine waste content shrinkage increased by 75 % for FA and AD mixes but by 300 % for CKD mixes, which showed the tendency of more shrinkage with CKD as fine waste. Above behavior of shrinkage was inversely related to the bleeding, since mixes with AD and FA had high bleeding and less shrinkage but CKD mixes had very less bleeding and maximum shrinkage. For lower bleeding, maximum drying of moisture would be from the bulk leading to more shrinkage unlike in high bleeding mixes leaving more water available for drying from surface.

Kuo et al. (2013) studied the drying shrinkage behavior of the CLSM mixes with addition of waste oyster shells (WOS) sand as 0-20 % replacement of natural fine aggregate. Shrinkage at 91 days observed as 0.12 % was highest for mix with 20 % WOS addition and minimum at 0.06 % for 0 % WOS which is just 50 % of the maximum. Higher shrinkage by addition of WOS was attributed to higher absorption rate of WOS resulting into higher water content in internal pores, and as a result more capillary pores participated in hydration process leading to higher shrinkage. Additionally, the lower modulus of elasticity of WOS compared to that of sand which was replaced resulted in a diminished resistance to shrinkage strain and led to higher shrinkage.

Mneina et al. (2018) in a study of CLSMs with addition of TOSW as replacement of fine aggregate (5-15 %) observed an increased ultimate drying shrinkage of 0.082 % for the mixes (having cement content of 60 kg/m^3) compared to 0.031% of the control mixes with no TOSW and to 0.072 % from 0.038 % for mixes with 90 kg/m^3. The reduced shrinkage with increased cement content was attributed to more hydration products leaving lesser spare water in the mix for evaporation thereby less shrinkage. Increased shrinkage with addition of TOSW was related to water/powder ratio and bleeding in the sense that mixes with higher bleeding would allow evaporation of water from surface and result into less shrinkage, and the addition of TOSW resulted into less bleeding, therefore more shrinkage. Also, fine TOSW particles caused refinement of the pore structure or led to fine capillary pores in the mix that enhanced the internal tensile forces resulting in more shrinkage.

Qian et al. (2019) in a study of shrinkage of the CLSM mixes by using excess excavated soil as replacement of sand with cement and fly ash as other constituents, reported that the shrinkage strain increased with higher cement and soil content or decreasing sand/soil ratio. This was attributed to higher water absorption by the soil and cement during hydration and evaporation of the same during drying caused more shrinkage.

2.4.6 Permeability

Permeability also known as hydraulic conductivity of the hardened CLSM is significant as it indicates the ability of the mix to allow leaking gases and liquids to pass through it. It tends to reduce with addition of finer and cementing materials while increase with addition of aggregates. High strength mixes that have more cementitious content show less permeability.

Naik and Singh (1997b) investigated the permeability of flowable slurries made using clean sand (FS1) and used foundry sand (FS2) as partial replacement of two types of Class-F fly ashes (F1 and F2), with cement content at round 40 kg/m^3 used in each mix as binder. Both foundry sands were progressively added in the mixes as 30, 50, 70 and 85 % replacement of the fly ashes in two sets of mixes i.e., one set for each fly ash F1 and F2. F1 fly ash had more percentage retained on no. 325 sieve and its quantity was also more than F2 fly ash in their respective mixes. Target flowability for F1 mixtures was 406 ± 25 mm and for F2 as 279 ± 50 mm. Permeability results for F1 mixes with 30-70 % and 85 % FS1 replacement respectively were ranging between (4.3-13.8) × 10^{-6} cm/sec and 74.2 × 10^{-6} cm/sec and for FS2 replacement were (5.6-11.1) × 10^{-6} cm/sec and 71.9 × 10^{-6} cm/sec. Similarly, in F2 fly ash mixes with 30-70 % and 85 % FS1 replacement were (8.3-13.4) × 10^{-6} cm/sec and 69.3 × 10^{-6} cm/sec and for FS2 replacement were (4.8-12.6) × 10^{-6} cm/sec and 64.9 × 10^{-6} cm/sec. Results indicated small positive effect on permeability by addition of foundry sand up to 70 %. However drastic change was witnessed at 85 % replacement. Increased permeability was attributed to increased voids due to addition of foundry sand and reduction of finer particles of fly ash, and also reduced pore refinement resulting from diminished pozzolanic activity by lesser fly ash in the mix. It was also observed that for up to 70 % FS addition, water to cementitious material ratio was between 0.40-0.80 which rose to 1.12-1.25 for 85 % FS replacement, therefore permeability was relatable to water to cementitious material ratio.

Lachemi et al. (2008) studied the effect of CKD addition upon the permeability of CLSM mixes designated as mix-1, mix-3, mix-8 and mix-10, with CKDs from four different sources, added at 4, 10, 15 and 30 %, where natural sand was used as fine aggregate. Reported permeability of around 2.38×10^{-5} cm/sec of the CKD based mixes was less than 1×10^{-4} cm/sec the level that differentiate the well or poorly drained strata. Therefore, the CKD mixes were termed as soil of very much lower permeability and also similar to compacted granular fill having permeability ranging between 10^{-5} to 10^{-4} cm/sec. It might be attributed to the fineness of CKD particles.

Her-yung (2009) studied the permeability characteristics of the CLSM due to glass-sand addition as normal sand replacement and due to variations of w/b. The permeability ratios observed were ranged as 1.03–0.69 %, 1.79–1.04 % and 2.57–2.02 % respectively against w/b ratio of 1.1, 1.3 and 1.5. This indicated that the permeability increased with an increasing W/B ratio. The higher w/b ratios meaning more water and less cement in any mix potentially enhance porosity and permeability. It was also observed that the permeability also reduces with increasing glass-sand percentage in the mix, that may be due to an effect of increased flowability rendering more excess water in the mix which again enhanced permeability.

2.5 HEAVY METAL TOXICITY

The CLSM are primarily used for backfill purpose, therefore the toxicity of CLSM becomes more relevant and important with regard to any possible leaching of harmful heavy metals into the ground and mixing with water posing health and environmental hazards.

Naik et al. (2001) investigated leaching assessment of flowable slurries prepared using clean sand (FS1) and used foundry sand (FS2) as partial replacement of two types of Class-F fly ashes (F1 and F2) along with cement. Foundry sands replaced fly ash by 30, 50, 70 and 85 % in two sets of mixes i.e., one set for each fly ash F1 and F2. Concentration in CLSM leachates regarding heavy metals, Fe, Ba, Mg, Zn, As, Cr, Pb, Se, Cd, Hg and Cl were determined and compared with enforcement standards (ES) and prevention action limits (PAL) of ground water quality system (GWQS) as well as drinking water standard (DWS). Mixes with F1 fly ash were tested and addition of clean foundry sand caused reduction of Se concentration up to 70 % FS1.

With absence of Se in FS1, the detected Se in CLSM was from cement and fly ash, however metal concentrations in all the mixes complied the ES and PAL of GWQS. Mixes with F2 complied with the ES and PAL of GWQS above 70 % foundry sand addition. In the F2 mixes up to 70 % foundry sand, Se concentration was above PAL, which was again attributed to contribution from cement and fly ash. Addition of clean or used foundry sand caused reduction of Se in CLSM making it environmentally safe for use.

Katz and Kovler (2004) studied the heavy metal leachability of the CLSM mixes and the mix having cement, industrial by-product coal fly ash (FA) as fine waste and crushed sand gave the worst results compared with sole fly ash. The relative leachability was checked for heavy metals as Ni, Li, Cr, Mn, Fe, Zn, B, Al, V, and Mo. Except Fe witnessing no change, rest of the metals showed a drop of about 11-85 % in their concentration in the CLSM with maximum drop of Zn and minimum for Al. The little or no drop for Al and Fe was attributed to presence of these metals in cement and crushed sand. Therefore, use of cement and crushed sand in the CLSM mixes caused a drop in heavy metal concentration of many metals.

Naganathan et al. (2012) investigated of toxicity of the CLSMs prepared with varying proportions of cement, BA and QD combined in different ratio as aggregate. Leachate was obtained while conducting toxicity characteristic leaching procedure (TCLP as per USEPA) on the 28 days CLSM specimens. Concentration of heavy metals like As, Ba, Cd, Cr, Pb, Hg, Se, and Ag in the leachate of CLSMs were examined. Comparison of the heavy metal concentration values was made against the allowable levels i.e., the threshold limits for hazardous substances as per Environmental Protection Agency, EPA-SW-846, 2000, 40 CFR, Part 261, 1986. The concentration levels of CLSM mixes were below the threshold values and thus were safe and did not pose any health or environmental problems making the CLSMs as non-hazardous. Also, the CLSM could be considered non-corrosive if pH value of its leachate is between 2 and 12.5. The pH value of the CLSM leachate ranged between 8.6-12.3 and therefore, CLSMs were considered non-corrosive.

Do et al. (2019) examined the toxicity of CLSM mixes (as per USEPA 1311) and observed the concentration of heavy metals in the leachate i.e., mercury (Hg) ranging between 0.043-0.050 mg/l, arsenic (As) 0.06-1.04 mg/l, chromium (Cr) 0.26-1.05 mg/l, cadmium (Cd) 0.03-0.13 mg/l and lead (Pb) N.D. (not detectable)-0.07 mg/l and found the levels within the specified regulatory levels of 0.2, 5, 5, 1, and 5 mg/l respectively given in the code of industrial wastes for landfill disposal. Accordingly, CLSM using fly ash (Fa), red mud (Rm), lime (L) and gypsum (G) as a cementless binder as Fa-RmLG along with pond ash as fine aggregate were considered to be safe and non-hazardous.

Mneina et al. (2018) studied the leachability characteristics of the CLSM mixes using TOSW as 15 % replacement of fine aggregate with cement and fly ash as other constituents. It was reported that TOSW have only little effect upon Li and Cr concentration of the mixes but at 28 days the higher concentration was only witnessed in mixes having fly ash and cement, since in raw TOSW, the concentration was below detectable limits. The concentration of As, Sr, Cd and Ba in the raw TOSW samples got reduced in CLSM mixes with cement and fly ash due to stabilization of the metals by cementitious materials. Higher Sr and Ba in mixes with fly ash replaced by TOSW i.e. reduction of cementing material also reflected a reduced stabilization of metals. However, Li and Cr were reduced by replacement of fly ash by TOSW compared with mixes having fly ash only indicating a contribution of these metals by the presence of fly ash itself.

Kim et al. (2018) in a leachability study of CLSM with binders, mine tailings and cement and fine aggregates pond ash and natural sand reported a higher concentration of As, Cu and Pb in CLSM than the regulatory limits as per US Code of Federal Regulations 40 CFR 268.40. The reason for this was stated to be equally higher concentration of these metals in raw tailings and pond ash. Therefore, limited use of combined pond ash and mine tailings in the CLSM was suggested.

Ho et al. (2022) studied the heavy metal toxicity of leachates from the CLSM mixes comprising waste water treatment sludge (WTS), NaOH based alkali accelerator, OPC and fly ash for the mixes with w/b of 0.65, WTS 0-80 % and accelerator as 5 %. The concentration of Pb, Cr, Cu, Zn, Cd and Ni were examined by the toxicity characteristics leachate procedure (TCLP). The maximum concentrations were witnessed for Cu as 0.06, for Cd as 0.01 and for Ni as 0.03 mg/l in with other metals being undetectable. The results were below the permissible regulatory limits of the respective metals at 15.0, 1.0 for Cu, Cd but none for Ni and WTS was suggested to be safe material for preparing CLSMs.

2.6 MINERALOGY AND MICROSTRUCTURE

2.6.1 Mineralogy of CLSM (XRD)

Zhen et al. (2013) examined the mineral phases through XRD scans of the hardened CLSM prepared using dewatered sludge (DS) and municipal solid waste incineration (MSWI) bottom ash and Calcium sulfoaluminate cement (CSA) as constituents. MSWI used was in oven dried at 65 degree C and milled condition (e.g. mixes I_{65}) and in further thermally treated at 900 degree C condition (e.g. mixes I_{900}). Mixtures were prepared by varying the DS: MSWI: CSA ratio wherein combined MSWI and CSA equaled DS by weight, but the MSWI and CSA further had mixture ratios 1/9, 4/6 and 8/2 (mixes I, II and III) in a way that MSWI increased. Reference mix was without MSWI. Similar mineral phases were seen in the milled MSWI CLSM mixtures with up to 40 % in MSWI-CSA combination (mix I_{65} and II_{65}) as in reference CLSM. With main peaks of crystalline phases such as quartz (SiO_2), ettringite ($C_3A.3CS.H_{32}$/ AFt), calcite ($CaCO_3$) with minor presence of anhydrite ($CaSO_4$) seen in CLSM, the good strength results were associated with presence of ettringite/AFt gels. Pertinently, higher addition of MSWI resulted in reduced intensity of ettringite and calcite peaks and increased quartz peaks leading to lower strength. Mineral phases in the thermally treated MSWI CLSMs were similar as in milled MSWI but with narrower and diminished peaks. In the case of 80 % thermally treated MSWI (mix III_{900}), the ettringite/AFt and calcite peaks were almost absent which was reflected by minimum strength. Formation of complex crystalline phases by thermal treatment was the reason for lowered strength due to lowered reactivity of MSWI ash that reduced its pozzolanic action with CSA.

Park et al. (2017) in a study of CLSMs comprising blast furnace slag, CFBC fly ash as binders, CBFC bottom ash (as aggregate), water content and NaOH (alkali activator), observed the disappearance of peaks of calcium-sources like calcium sulfate, lime of the raw materials, replaced by peaks of hydration products like ettringite, portlandite and gypsum in mixes with 2.5 level of bottom ash similar to the mix with 0.3 (30 % of the binder) level of slag. Presence of ettringite peak at 56 days reflected availability of sulfate ion (SO_4^{-2}) from CFBC fly ash and bottom ash in the 2.5 level of aggregate mix, and this is supported by the decrease of gypsum peak at 2θ -11.6^0 and increase in ettringite peak at 2θ -9.12^0. Higher strength development at 56 days in higher aggregate (2.5 level) mix correlated with the above phenomenon. However, the peaks of gypsum and ettringite reduced at 56 days in 0.30 level slag mix reflected insufficient sulfate availability due to replacement of CFBC fly ash by slag and due to change of ettringite phase to calcium monosulfoaluminate hydrate. With the presence of calcite and portlandite, the increased calcite peak in the mixes at 56 days reflected the carbonation reaction due to curing process in unsealed condition.

Wang et al. (2018) studied the effect of alum sludge as replacement of recycled fine aggregate in CLSM mixes comprising OPC along with SCM pulverized fly ash (PFA) as binders. It was reported that 12.5 % addition of alum sludge caused disappearance of $Ca(OH)_2$

peak at 2θ 18.4° present in the 0 % sludge CLSM sample which was validated by reduction of CH from 6.7 % to 1.1 % in the quantified results. Further, existence of gentle peaks of unreacted alite and belite seen in the CLSMs with sludge represented delayed setting and low strength gain.

Do et al. (2019) examined the mineral phases through XRD of the 28 days CLSM mixes in a study of CLSM mixes prepared using fly ash (Fa), red mud (Rm), lime (L) and gypsum (G) as a cementless binder as Fa-RmLG along with pond ash as fine aggregate. Hydration activity was represented by existence of ettringite and CSH peaks and quartz and dehydrate gypsum peaks represented the unreacted minerals from pond ash and gypsum in the mixes. Mix with high gypsum resulted into existence of high intensity peak of gypsum and ettringite owing to availability of more sulfate ions from gypsum reacting with alumina from fly ash to form ettringite at 2θ 29°. The addition of high fly ash content resulted into the increased CSH peaks at 2θ 16°, 41° due to silica-aluminous phase from fly ash at these locations and quartz peak at 2θ 29° as residue mineral. Addition of lime content resulted in more hydroxyl ions in the mix followed by fly ash hydration and formation of CSH and calcite minerals represented by increased peaks at 2θ 29° along with a subdued quartz peak at 2θ 26°.

Ho et al. (2022) compared the mineralogy of the CLSM mixes comprising contents of 0-80 % waste water treatment sludge (WTS), NaOH based alkali accelerator factor A as 5 %, OPC and fly ash with w/b of 0.65. XRD results showed main peaks representing phases of portlandite ($Ca(OH)_2$), quartz (SiO_2) and CSH in CLSM mixes with WTS 0-80 %. Presence of higher peaks of portlandite in 80 % WTS than 20-40 % WTS was considered as an indication of more pozzolanic activity in 20-40 % WTS mixes with associated higher strength. The higher quartz peaks were also associated with higher WTS content in the mixes. Earlier, Hwang et al. (2017) in a study of CLSM observed diminished peaks of constituents GGBFS, FA and WTS due to reaction with alkali activator NaOH solution. With primary presence of crystalline silica SiO_2 and diffused halo of CSH in XRD scan of CLSMs, reduction of CSH peaks and increased silica peaks were seen with addition of WTS. Reduction of CSH was attributed to reduction of GGBFS and related hydration reaction by addition of WTS.

2.6.2 Microstructure (SEM, EDS)

Zhen et al. (2013) examined the microstructure through SEM and EDS of the hardened CLSM having dewatered sludge (DS) and municipal solid waste incineration (MSWI) bottom ash and Calcium sulfoaluminate cement (CSA) as constituents. Observation of good AFt crystals having polygonal structure in the milled MSWI mix (DS: MSWI: CSA ratio

1.0:0.1:0.9), I_{65} was said to be reflection of crystallochemical incorporation that converted DS and MSWI wastes from amorphous to crystalline form. The formation of AFt phases among various particles enhanced the contact between solid phases leading to densification of the mix and higher strength. At increased MSWI levels in mix II_{65}, (DS: MSWI: CSA ratio 1.0:0.4:0.6), unchanged particles of DS and MSWI identified as loosely positioned near un-hydrated clinker, and minor presence of important hydration compounds like AFt and $CaCO_3$ reflected substantial inhibition of cement hydration. The microstructure of the thermally treated MSWI CLSM mixes was loose, rough and without presence of crystalline AFt and calcite making it un-favorable for compacting. The microstructure was differentiable by the embedded surface characteristics of the MSWI particles, as the heating at 900^0C caused formation of vitreous/impervious layers upon surface that prohibited transport of ion and water for strength gain and resulted into porous structure with lower strength.

Kuo et al. (2013) studied the microscopic interfacial properties of the CLSM mixes with addition of waste oyster shells (WOS) sand as 0-20 % replacement of natural fine aggregate. The mix with 0 % WOS at 7 days was marked by presence of flaky CH crystals, irregular rose shaped AFm phases seen all around and absence of CSH due to inadequately dense structure with pores made by high water/binder. At 28 days formation of CSH gel due to continued hydration, along with a reduced porosity was seen reflecting an increased compressive strength. WOS mixes at 7 days had laminar CH and net-structured CSH gel along with flakes of WOS sand in loose structured system indicating low interfacial cementing, and at 28 days presence of the rows of strips with indentations and cracks upon the WOS sand surface representing poor binding between WOS and mortar which caused drop in strength.

Do et al. (2019) studied the microstructure based upon SEM images of the 28 days CLSM mixes prepared using fly ash (Fa), red mud (Rm), lime (L) and gypsum (G) as a cementless binder as Fa-RmLG along with pond ash as fine aggregate. The SEM images in general presented the hydration of the fly ash particles reflected by existence of bonding gels wrapped upon the surface, with different characteristics depending upon the matrix proportions as well as the curing age. At 3 days even with high lime content in the mix the bond gels over fly ash particles were thin showing much less development of hydration reaction but at 28 days mixes showed development of needle shaped ettringite and amorphous CSH as mark of further hydration of fly ash particles. Large amount of gypsum in the mix reflected thicker and dense long needle shaped ettringite leading to higher compressive strength compared to thin, long needle with low gypsum content. Increased fly ash in the mixes showed network shaped gel structure. High lime content resulted into thick needles shaped dense ettringite and higher CSH gel filling the voids leading to improved strength.

Ho et al. (2022) examined the microstructure through SEM and EDS scan of the CLSM mixes comprising contents of 0-80 % waste water treatment sludge (WTS), NaOH based alkali accelerator factor A as 5 %, OPC and fly ash with w/b of 0.65. The SEM images reflected the reactions upon the particle surface and edges showing activation of base materials by cement and alkali accelerator. Microstructure of 0 % WTS mix depicted large gaps between fly ash particles, which densified at 20-40 % WTS with the development of CSH and CASH validated by the higher strength of the mixes. Visibility of unreacted particles of FA, partially reacted WTS particles and small amount of cementitious compounds like CSH/CASH were reflected in porosity of 80 % WTS mixes compared to 0/20/40 % WTS. EDS results in regard to concentration of Al and Si in the mixes were studied where higher WTS content showed higher Si/Al ratio and lower strength. Earlier, Hwang et al. (2017) studied microstructure of CLSM with addition of 0-20 % WTS as percentage of GGBFS plus FA, while using NaOH solution as an alkali activator. SEM images similarly showed stimulated source materials represented by reaction on the surface and edges of particles. Images with WTS showed denser microstructure unlike isolated reaction products seen with large gaps in CLSM without WTS. Also, presence of CSH gel in WTS CLSM represented an acceleration of reaction by WTS. Decreasing Si/Al ratio from EDS results showed the increased compressive strength with addition of WTS in the alkali activated mix.

2.7 SUMMARY

The above literature review gives an overview of the many CLSM studies involving use of different by-product materials from a wide range of industries as constituents for the development of CLSMs. The physical as well as chemical characteristics of the constituent materials have impacted the properties of the mixes in plastic and hardened state. Prominent factors related to constituents such as particle shape, fineness, porosity, surface texture, water absorption, water affinity, specific gravity, paste volume ratio, w/cm, pc/cm, better packing, reduced interference between coarser constituents, reactivity of constituent, pozzolanicity, alkali activator molarity, irregularity of particles, hydration capacity, inertness, water demand, filler cohesiveness, organic content, impact absorption resistance, curing age, bond, modulus of elasticity and refinement of pore structure have impacted the properties of the CLSM.

2.7.1 Requirement of present study

Literature review presents only a few studies (Katz and Kovler, 2004; Lachemi et al., 2010, 2008; Taha et al., 2007) have explored use of CKD, SCMs and small or no amount of cement as binders in CLSMs. More study for maximising utilization of CKD in CLSM was required. Also only a few studies present use of spent foundry sand as partial replacement of fine aggregate in CLSM (Deng and Tikalsky, 2008; Dingrando et al., 2004; Naik et al., 2001; Naik and Singh, 1997a). CLSMs having major proportions of fine aggregates, use of spent foundry sand as fine aggregate replacement in CLSM is required to explored to maximize its utilization. Again, the literature showed rare studies (Islam and Hossain, 2019; Nataraja and Nalanda, 2008) regarding use of RHA in CLSM. Nataraja and Nalanda (2008) used RHA as a substitute for aggregate in CLSM with processed RHA by grinding. Use of unprocessed RHA in as received condition was required to be explored. Although studied individually, combined utilization of two or more of these industrial by-products as complete replacement of conventional constituents in the development of CLSM needed to be explored further. Above research gap required evaluation of utilization potential of industrial by-products CKD, SFS, and RHA for developing CLSM through investigation of engineering properties of CLSM in fresh and hardened state including assessing its leachability characteristics for ensuring environmental safety aspect of using such materials for various application.

The present study sought to use industrial and agro-based or biobased by-products such as cement kiln dust, spent foundry sand and unprocessed rice husk ash either as binder or aggregate in the CLSM. CKD with composition similar to cement is proposed to be used as partial to full replacement of cement as binder. Other by-products spent foundry sand and unprocessed rice husk ash are proposed to be used as complete replacement of conventional fine aggregate. Different combinations of these materials in varying quantities have been proposed for experimentation in this study.

Chapter 3

EXPERIMENTATION PROGRAMME

3.1 GENERAL

Objective of the present study was to explore development of controlled low strength material fulfilling the industry standards suitable for backfill applications, by utilizing industrial and agro/biobased by-products. Use of by-products is advantageous as it reduces use of virgin raw materials or manufactured materials on one hand and conserve the already stressed landfill space which would otherwise be required for disposal of the unutilized by-product. Further, use of by-products also reduces pressure upon depleting natural resources required for raw materials for direct use such as aggregates or for further processing in manufacturing industry. CLSM is used in many applications that require certain essential fresh and hardened state properties which are in an overlapping zone of soil and concrete (Parhi et al., 2023). These are mainly termed as fresh/plastic state and hardened/in-service state. Flowability and compressive strength are the most important characteristics of any CLSM. Flowability makes the CLSM self levelling which ensures easy placement of the CLSM in to narrow sites without requirement of any compaction and strength ensures achievement of bearing capacity to support loading. Excavatability is another important aspect of CLSM intended to be used for utility trenches since it would allow excavation in future in an event of repair or maintenance of embedded pipeline, cable etc. ACI 229 R defines maximum 28 days unconfined compressive strength for CLSM as 8.30 MPa, and for it to be excavatable, 2.1 MPa is the maximum strength. Aim was to develop CLSM with acceptable fresh and hardened state characteristics along with maximizing use of by-products in pursuit of sustainability. Additionally, impact of CLSM upon environment in terms of toxicity by leachate from the CLSM and ecological parameters i.e., embodied energy and carbon dioxide were also kept in view.

3.2 MATERIALS

Conventional CLSMs use (a) cement as binder that provides cohesion and strength, (b) fly ash or other similar materials for flowability and increasing strength and reducing bleeding, shrinkage and permeability (c) admixtures for controlling workability, shrinkage, bleeding, segregation, density, thermal insulation, freeze thaw properties and strength development (d) other additives to achieve waste stabilization, controlling permeability and other specific results (e) water for workability (f) aggregates i.e. granular excavation material with lower quality properties as major constituent affecting flowability and strength. Coarse aggregates are not generally used in CLSM. The CLSM, due to their specified low strength limits, do not require virgin materials and allows even low-quality materials as input constituents for the mixes. Some non-standard materials that are locally available, economical can also be accepted as constituent based upon their testing for suitability. By-products from different industry and agro/biobased sector can be potential input materials for the CLSM. Different supplementary cementing materials (SCM) like slags, red mud, cement kiln dust, wood ash, bagasse ash, circulating fluid bed combustion ash (CFBC) etc. have been used as binder in CLSM (Parhi et al., 2023). Apart from binders, natural aggregates along with by-products from different industry/sector such as various bottom ash, waste foundry sand, recycled concrete aggregate (RCA), pond ash, crumb rubber, scrap tire, glass waste, quarry dust, sludges etc. have been used as fine aggregate or filler in CLSM.

In present study, materials under study are two industrial by-products namely cement kiln dust (CKD) and spent foundry sand (SFS) and an agro/biobased by-product named rice husk ash (RHA); which have been used for checking their feasibility of their use in the development of CLSM. The CKD, which is a by-product from the cement manufacturing process has been used as binder along with ordinary Portland cement (OPC) as partial to full substitute of cement. The SFS and RHA, which are by-products respectively from metal casting and biobased material used as fuel, have been used either singly or in combination as full substitute of natural fine aggregate. Characteristics of the constituents of CLSM are discussed in following section.

3.2.1 Ordinary Portland Cement (OPC)

Ordinary Portland Cement (OPC), 43 grade, conforming to IS:269 (IS: 269, 2015) have been used as binder along with CKD. Chemical composition of the OPC was analyzed by X-ray fluorescence (XRF). Result along with standard requirement for OPC as per the relevant code (IS 269) are presented in Table 3.1. The chemical composition of the OPC is in accordance with the specified limits. The Blaine fineness test is the most commonly adopted procedure for finding OPC fineness. This test measures the surface area of the cement particles per unit mass in an indirect manner. Blaine's fineness of OPC in this study worked out as per IS 4031 (Part 2) (IS:4031(Part-2), 1999) is 3300 cm^2/gm. Blaine's fineness of OPC is more than 2250 cm^2/gm which is in accordance with the provision of IS:269 2015. Similar range of 3000–5000

cm^2/gm is also reported in literature (Ahadzadeh Ghanad and Soliman, 2021; Kumar et al., 2021; Mithun and Narasimhan, 2016). Physical properties of cement, specific gravity, Blaine's fineness, initial and final setting time, compressive strength at 7 days and 28 days that were determined as per relevant code have been presented at Table 3.2.

Table 3.1 Chemical composition of Ordinary Portland Cement (OPC)

Compound	Present study (%)	Provision as per (IS:269 2015, 2015)
SiO_2	21.92	-
Al_2O_3	3.39	Al_2O_3/ Fe_2O_3=1.28 is > 0.66 (Min)
Fe_2O_3	2.65	
CaO	62.24	Ratio of percent lime to percent of silica, alumina and iron oxide i.e., [Cao - 0.7 SO_3]/ [2.8 SiO_2 + 1.2 Al_2O_3 + 0.65 Fe_2O_3] = 0.906 is between 0.66-1.02
MgO	3.25	6.0 (Max)
SO_3	1.99	3.5 (Max)
Na_2O	0.61	-
K_2O	0.39	-
MnO	0.11	-
LOI	3.44	5.0 (Max)

Table 3.2 Physical properties of Ordinary Portland cement (OPC)

Property	Value in present study	Provision as per (IS:269 2015, 2015)	Code
Specific gravity	3.10	-	(IS:4031 (Part-11), 2013)
Blaine's fineness	3300 cm^2/gm	2250 cm^2/gm (Min)	(IS:4031(Part-2), 1999)
Initial setting time	75 minutes	30 (Min)	(IS 4031(Part 5):1988, 1988)
Final setting time	230 minutes	600 (Max)	(IS 4031(Part 5):1988, 1988)
Compressive strength (7 days)	34 MPa	33 MPa (Min)	(IS 4031(Part 6):1988, 1988)
Compressive strength (28 days)	45 MPa	43-58 MPa	(IS 4031(Part 6):1988, 1988)

The specific gravity of cement is 3.10 which is around the general value of 3.15 for OPC reported in literature (Khanna, 2009). Further initial and final setting time values of 75 minutes and 230 minutes are in compliance with the provisions of IS 269. Similarly, compressive strength values for OPC also are in accordance with the provisions of IS 269.

3.2.2 Cement Kiln Dust (CKD)

CKD was sourced from a reputed cement manufacturing unit situated at Darlaghat, Himachal Pradesh, India and used throughout in the entire study, which as shown at Figure 3.1 has a tan colour tone. CKDs has been known to have a grey to tan color (Kunal et al., 2012). CKD has been used in present study as partial to 100 % replacement of OPC.

Figure 3.1 Cement Kiln Dust (CKD) used in the study

Chemical composition of the CKD was also examined with XRF technique also. The results of XRF scan are presented at Table 3.3 along with values reported in many studies. In this study, the lime (CaO) is the major component in CKD followed by quartz (SiO_2), Al_2O_3 and Fe_2O_3. Also, CKD has a higher content of SO_3 than that in OPC. Presence of alkalis Na_2O and K_2O is also prominent, which is also similarly reflected by past studies in literature. Higher alkalis and sulfur in CKD are the reason for its removal from kilns. Similarly, loss on ignition (LOI) in CKD is 22.2 % which is also very high as compared to 3.44 % for cement. This is comparable with the results reported in many studies. It is to be noted that LOI is representative of volatile matter, CO_2 and moisture (Khanna, 2009).

Table 3.3 Chemical composition of Cement Kiln Dust (CKD)

Compound	Present study (%)	As reported in literature (%) (Kalina et al., 2018; Kunal et al., 2014; Lachemi et al., 2008; Maslehuddin et al., 2008)
SiO_2	14.25	10.00-18.60
Al_2O_3	5.01	2.38-5.50
Fe_2O_3	3.51	1.90-2.89
CaO	39.66	49.30-80.70
MgO	1.63	0.69-3.30
SO_3	6.00	1.13-11.10
Na_2O	5.11	0.20-3.84
K_2O	0.32	1.12-16.90
MnO	1.52	-
LOI	22.20	3.10-15.80

Mineralogy of the by-product constituent materials was examined through X-ray diffraction (XRD) technique. X-ray Diffraction (XRD) scanning was conducted with a Panalytical's X'Pert Pro X-Ray Diffractometer on powdered samples. Scanning was performed in the 2θ range of 10º-90º with a scan rate of 0.02º per second. The diffraction data has been evaluated by means of X'pert Highscore Plus software for mineral phase identification. Analyzed X-ray Diffraction (XRD) plot of CKD shown at Figure 3.2. XRD graph peaks signify presence of calcite ($CaCO_3$), quartz (SiO_2), wollastonite ($CaSiO_3$) phases in significant amount and a small amount of magnetite (Fe_3O_4) and C60 phases in CKD. Calcite forms the major phase of CKD followed by quartz, wollastonite and magnetite.

Characterization of CKD was also done by using scanning electron microscopy (SEM) and Energy dispersive X-ray spectroscopy (EDS) techniques. The SEM image is shown at Figure 3.3 (a). Particles of CKD are seen as irregular and less than 20 µm in size**.** Energy dispersive X-ray spectroscopy (EDS) scan of CKD is shown at Figure 3.3 (b). This presents existence of oxides of elements Ca, Si, Mg, Al and Fe. Potassium and sulphur oxides represent higher alkalis in the chemical composition of CKD similarly as reported earlier (Kunal et al., 2012).

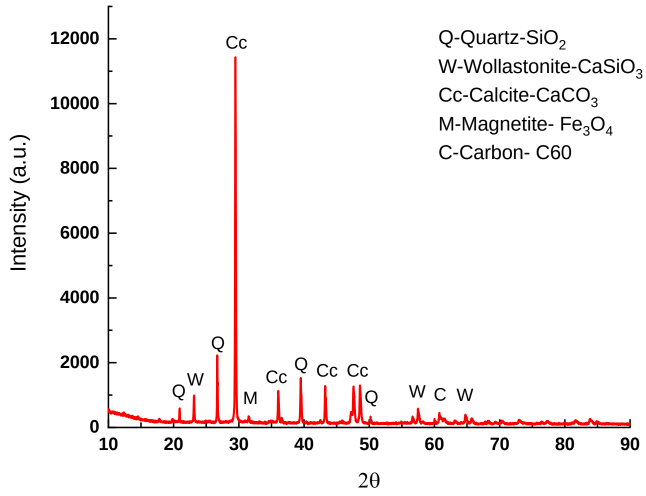
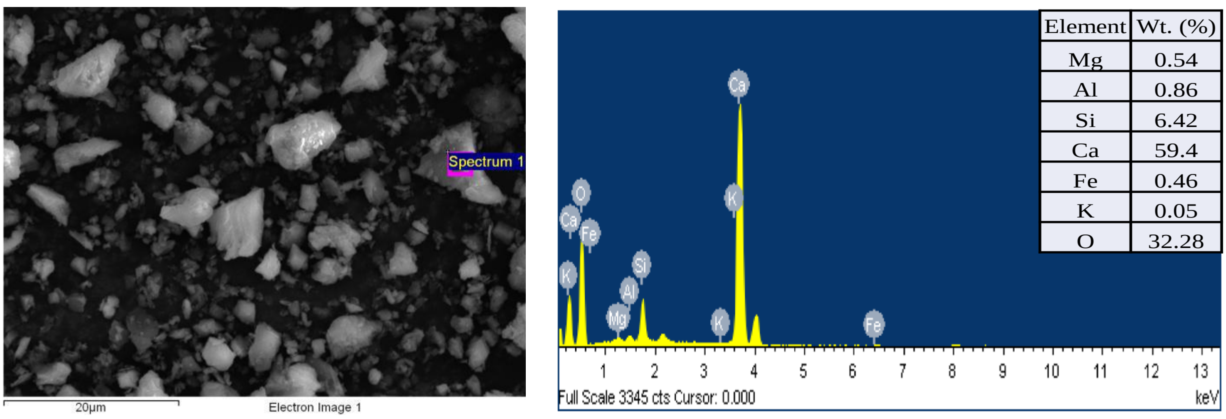


Figure 3.2 XRD scan of Cement Kiln Dust (CKD)



(a) (b)

Figure 3.3 Characterisation of Cement Kiln Dust (CKD) (a) SEM image (b) EDS scan

Physical characteristics, Blaine's fineness and specific gravity of the CKD were determined similarly as for OPC. Blaine's fineness value of CKD as determined in this study was 6070 cm^2/gm. A Blaine's fineness value range of 3180-14000 cm^2/gm is also previously reported in literature (H. Hassan et al., 2013; Khanna, 2009). Comparing the Blaine's fineness values of binder materials in the study, CKD is much finer than OPC. The specific gravity of CKD was determined as 2.57. Further, comparison of specific gravity values of both, it revealed that the CKD is lighter due to its lower specific gravity than OPC.

3.2.3 Spent Foundry Sand (SFS)

Spent foundry sand (SFS) was obtained from an automobile parts manufacturing unit situated at the town of Kurali near Chandigarh in Punjab, India. The metal being cast is grey iron and foundry sand for the moulding process used bentonite as binder and coal dust for better finish of the cast metal. Depending upon the binder system used for mould preparation, there are two types of foundry sands i.e., green sand and chemically bonded sand (Bhardwaj and Kumar, 2017). The foundry sand is classified as green sand when clay is used as binder or as chemically bounded sand in case of chemical as binder. Green sand is black or gray in colour while chemically bounded sand is medium tan, off white or light coloured. It has been observed that the foundry sand used throughout the present study is black colored as shown in Figure 3.4. Black color signified sand to be green foundry sand using clay as binder and the presence of carbonaceous substance has imparted black color to the spent foundry sand.

Figure 3.4 Spent foundry sand (SFS) used in the study

The quantitative analysis for chemical composition of the SFS was done through XRF and is presented in Table 3.4. The SFS has a major proportion of Silica oxide (SiO_2) at 75.48 % followed by smaller percentage of the compounds Fe_2O_3 at 13.54 %, Al_2O_3 at 3.80 %, SO_3 at 3.06 % MgO at 1.24 % and CaO at 0.52 %. Traces of alkali compounds such as Na_2O and K_2O were also seen. The quantity of different compounds in the SFS is well withing the range of the compounds reported in literature shown in Table 3.4.

XRD analysis of SFS is shown at Figure 3.5. The XRD scan depicting minerology shows SiO_2 as the prominent peak represent quartz as the dominant phase. Small presence of other phases of minerals like sulphur, zeolite and carbonyl iron sulphide are also seen. SEM image is showing the magnified morphology of SFS particles at Figure 3.6 (a). EDS scan of SFS is presented at Figure 3.6 (b) also shows major presence of Si and O representing SiO_2. SEM image shows the most of the SFS particles to be sub-angular to round shape particles.

Surface texture appears to be rough. As per literature also, the SFS particles are usually sub-angular to round shaped (Kumar and Parihar, 2021).

Table 3.4 Chemical composition of spent foundry sand (SFS)

Compound	Results in present study (%)	Range (%) in literature (Basar and Aksoy, 2012; FHWA, 2016a; Kumar and Parihar, 2021; Singh and Siddique, 2012; Tikalsky et al., 2004)
SiO_2	75.48	64.80-98.00
Al_2O_3	3.80	0.17-10.41
Fe_2O_3	13.54	0.29-11.39
CaO	0.52	0.00-21.80
MgO	1.24	0.00-2.32
SO_3	3.06	0.00-3.00
Na_2O	0.80	0.01-2.11
K_2O	0.02	0.00-2.13
TiO_2	0.51	0.00-1.61
MnO	0.14	0.01-0.21

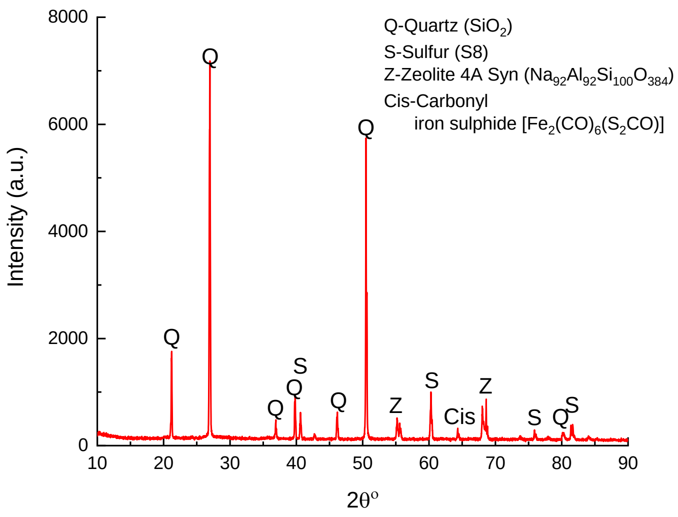
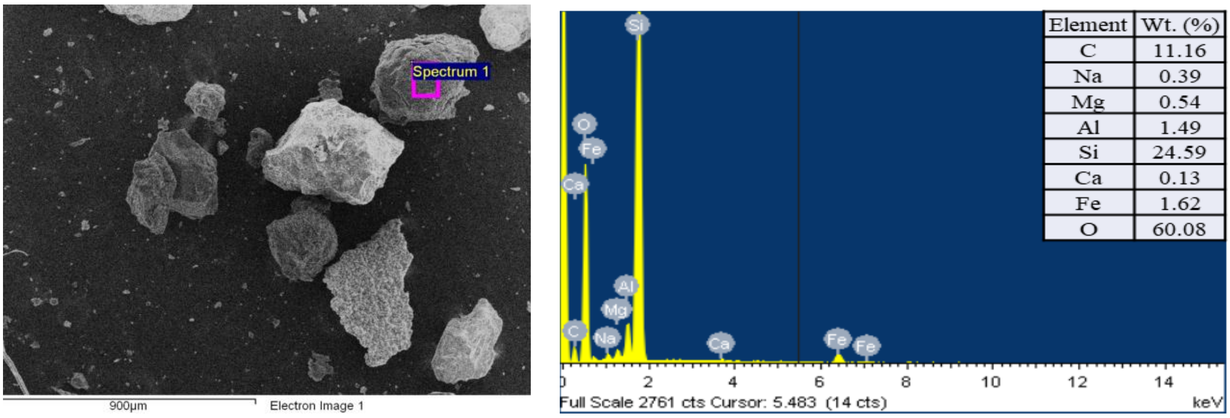


Figure 3.5 XRD scan of Spent Foundry Sand (SFS)

Physical properties such as bulk density, specific gravity, water absorption of SFS were determined as per relevant standards and are presented in Table 3.5 along with typical values reported in literature. It is also important to be noted that the spent foundry sand can't be governed by the Indian standard for natural fine aggregate, i.e., IS:383 2016 (Bureau of Indian Standards, 2016). It is in view of the fact that the spent foundry sand is size specific and its properties vary from source to source depending upon, additives used in mouldings, binder, and number of recyclings the sand has undergone before being discarded as waste foundry sand.



(a) (b)

Figure 3.6 Characterisation of Spent Foundry Sand (SFS) (a) SEM image (b) EDS scan

Table 3.5 Physical properties of Spent Foundry Sand (SFS)

S. No.	Property	Relevant code	Value of present study	Typical values reported in literature (Bhardwaj et al., 2022; FHWA, 2016a; Kumar and Parihar, 2021; Siddique and Kadri, 2011; Tikalsky et al., 2004)
1.	Bulk Density / Unit weight -oven dried (kg/m^3)	(IS:2386-Part III, 1963)	1425	1538-1784
2.	Specific gravity SSD	(IS:2386-Part III, 1963)	2.51	2.39-2.55
3.	Apparent specific gravity	(IS:2386-Part III, 1963)	2.62	-
4.	Water absorption (SSD) %	(IS:2386-Part III, 1963)	2.67	0.40-5.00

Curve plot of particle size distribution of SFS in this study alongside ASTM standard grading requirement for regular sand is shown in Figure 3.7. Sizes corresponding to 60 %, 30 % and 10 % particles finer than, D_{60}, D_{30} and D_{10} and related parameters, coefficient of uniformity C_u and Coefficient of curvature C_c along with fineness modulus FM are also presented at Table 3.6.

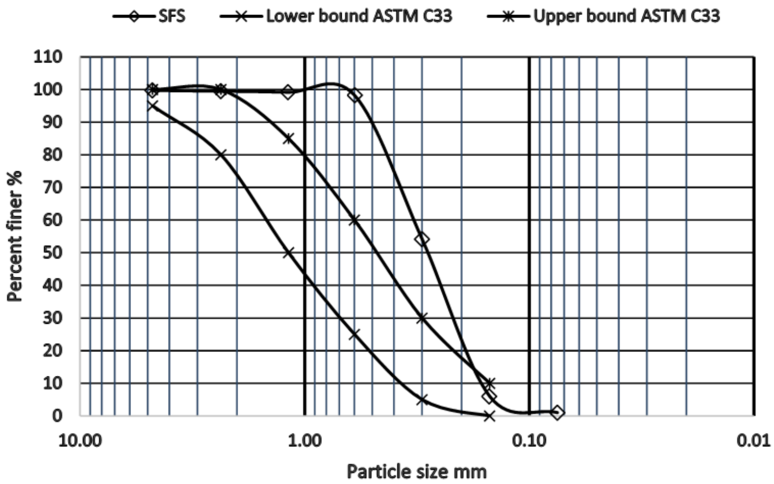


Figure 3.7 Particle size distribution of Spent Foundry Sand (SFS)

Based on ASTM guidelines, the coefficient of uniformity C_u value of 2.08 (less than 6) and coefficient of curvature C_c of 0.915 (not between 1 and 3), suggest that SFS is poorly graded (ASTM D2487, 2000; Tikalsky et al., 2004). Particle size distribution curve of SFS, not between the curves representing the bounds of well graded sand as per ASTM C33 (ASTM C33/C33M, 2011), also shows the SFS to be not well graded. As per particle size distribution, 90% of the SFS particles fall between 0.15 mm (5% quantile) - 0.55 mm (95 % quantile). It means that the grain size distribution is uniform. Similar observations about uniform grain size distribution of SFS have been also reported in literature, as per which grains size are quite uniform with 85-95 % material between 0.6 and 0.15 mm and 5-12 % below 0.075 mm (Bhardwaj and Kumar, 2017). Fineness modulus (FM) of 1.43 of the SFS in present study is within the range of 1.30-2.35 reported in literature for waste foundry sands. Further, the FM of SFS is much less compared to range of 2.3-3.1 reported for normal sand. For this fact, it is considered to be too fine and therefore is not considered suitable as replacement of natural sand at higher levels. Specific gravity of the SFS in present study is 2.51 which is in line with that reported in literature as between 2.39-2.55. Similarly, the water absorption 2.67 % is also within to the literature reported range of 0.40-5.0 % for spent foundry sands.

Table 3.6 Particle size related parameters of Spent Foundry Sand (SFS)

S. No.	Property	Relevant code	Value of present study	Typical values in literature (Bhardwaj et al., 2022; FHWA, 2016a; Kumar and Parihar, 2021; Siddique and Kadri, 2011; Tikalsky et al., 2004)
1.	Fineness modulus (FM)	(IS:2386-(Part-1), 1963)	1.43	1.30-2.35
2.	60 % finer than -D_{60} (mm)	(ASTM D2487, 2000)	0.34	0.20-0.41
3.	30 % finer than -D_{30} (mm)	-do-	0.23	0.14-0.32
4.	10 % finer than -D_{10} (mm)	-do-	0.16	0.08-0.21
5.	Coefficient of uniformity $C_u = D_{60} / D_{10}$	-do-	2.08	0.90-41.50
6.	Coefficient of curvature $C_c = [D_{30} \times D_{30}] / [D_{10} \times D_{60}]$	-do-	0.92	0.85-18.00
7.	% Finer than 75µm	-do-	1.02	-

3.2.4 Rice Husk Ash (RHA)

RHA was sourced from another industrial unit producing chemicals situated at Dera Bassi, Punjab where rice husk was used as a fuel for heating purposes. Rice husk, a prominent biomass available in abundance worldwide (Manu et al., 2023), is the outer shell for the rice grain. Due to its high calorific value (Della et al., 2002; Yu, 2014), it is generally used as fuel in boilers in the various industries resulting into generation of RHA. RHA in the study was used in as received and unprocessed condition, which is shown in Figure 3.8. It is more or less black colored. As per literature colour varies from white to grey to black depending upon the concentration of carbon, where high carbon is reflection of insufficient burning (Endale et al., 2022; Wang et al., 2021). Therefore, RHA in present study is not properly burnt one.

The quantitative analysis for chemical composition of the RHA done through XRF technique is presented in Table 3.7. The RHA contains major proportion of Silica oxide (SiO_2) at 93.34 % followed by smaller percentage of the compounds SO_3 at 3.26 %, Fe_2O_3 at 0.75 %, MgO at 0.50 %, Al_2O_3 at 0.31 %, and CaO at 0.23 %. Traces of alkali compounds such as Na_2O and K_2O were also observed in RHA similar to as seen in SFS. It can be seen that the quantity of different compounds in the RHA is around the similar range of those compound as reported in literature.

Figure 3.8 Rice Husk Ash (RHA) used in the study

Table 3.7 Chemical composition of Rice Husk Ash (RHA)

Compound	Results in present study (%)	Range (%) in literature (Anwar Hossain, 2011; Chopra et al., 2015; de Sensale et al., 2008; Fapohunda et al., 2017; Thiedeitz et al., 2022)
SiO_2	93.34	86.00-94.97
Al_2O_3	0.31	0.20-5.00
Fe_2O_3	0.75	0.10-2.00
CaO	0.23	0.50-2.93
MgO	0.50	0.10-2.10
SO_3	3.26	0.16-0.30
Na_2O	0.10	0.05-0.70
K_2O	0.40	0.10-2.30
MnO	0.20	0.00-0.20

XRD analysis of RHA is shown at Figure 3.9. The XRD scan depicting minerology shows quartz, tridymite and zeolite as the dominating silica compound with prominent peaks. Presence of other phases of mineral compounds of sulphur and aluminium are also seen. The XRD scan shows no sharp peaks but a broad band between 15 – 30° (2-theta) on the curve along with certain content of tridymite, quartz, which means that the RHA may be amorphous in nature and is obtained by burning at high temperature (800-1000° C) leading to crystallization of the amorphous silica. Cizer et al. (2007) and Vasavi and Indrajith Krishnan (2016) in their study of properties of RHA, have also interpreted similar XRD scan as amorphous. This is attributed to creation of local high temperatures as a result of uncontrolled burning regime. SEM image is showing the magnified morphology of RHA particles at Figure 3.10 (a). This shows RHA particles to be irregular, highly porous and vesicular particles (Endale et al., 2022). Surface texture is having serrations with ridges, valleys of non-uniform length. EDS scan of RHA is shown at Figure 3.10 (b) which shows presence of the oxides of C, Mg, Si, K, Ca, Cu and Zn with major content of Si and C. The range of elements Si and O of the EDS scan of this study is nearly same as reported for amorphous RHA in literature (Vasavi and Indrajith Krishnan, 2016). This is also reflected in the composition results through XRF.

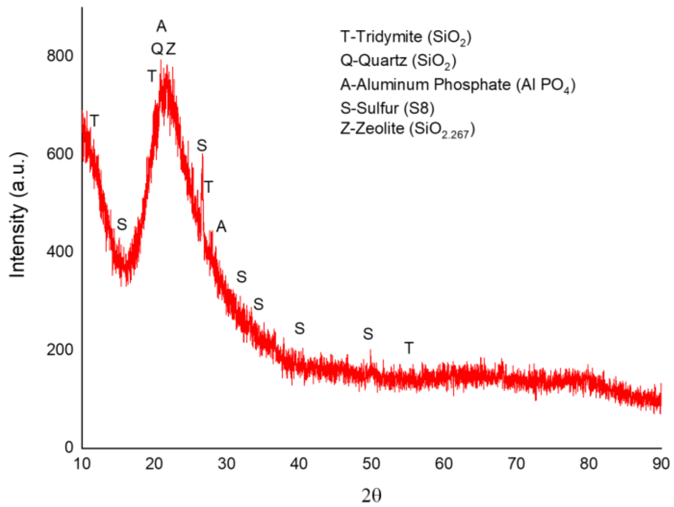
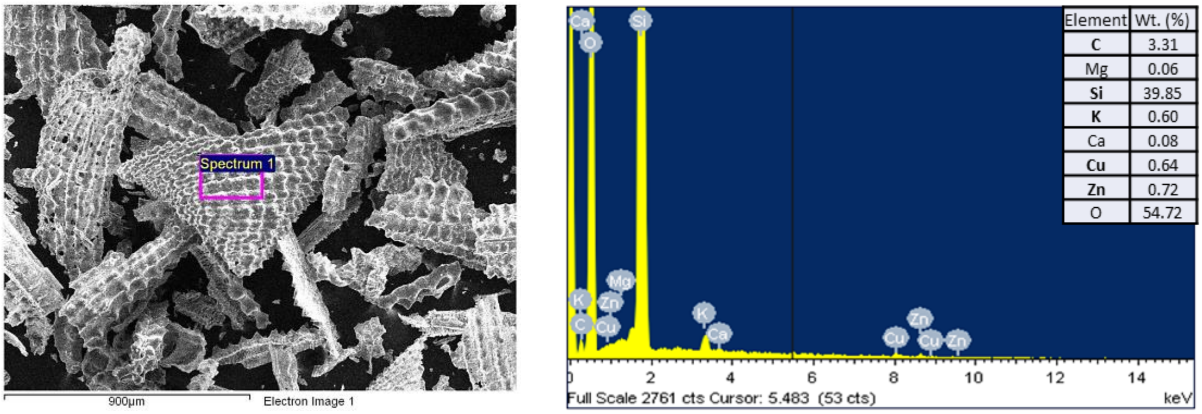


Figure 3.9 XRD scan of Rice Husk Ash (RHA)

Physical properties such as bulk density, specific gravity and water absorption of RHA were determined as per relevant standards and are presented in Table 3.8 along with typical values reported in literature. Specific gravity of the RHA in present study is 1.51 which is less than 2.51 of SFS. This shows RHA to be lighter than SFS. Similarly, the water absorption 36.61

% is very high and is due to high porosity of RHA owed to its vesicular nature, and much higher than 2.67 % of SFS.



(a) (b)

Figure 3.10 Characterisation of Rice Husk Ash (RHA) (a) SEM image (b) EDS scan

Table 3.8 Physical properties of Rice Husk Ash (RHA)

S. No.	**Property**	**Relevant code**	**Value of present study**	**Typical values reported in literature (de Sensale et al., 2008; Fapohunda et al., 2017; Thiedeitz et al., 2022)**
1.	Bulk Density / Unit weight -oven dried (kg/m^3)	(IS:2386-Part III, 1963)	246	-
2.	Specific gravity SSD	(IS:2386-Part III, 1963)	1.51	2.05-2.53
3.	Apparent specific gravity	(IS:2386-Part III, 1963)	1.85	-
4.	Water absorption (SSD) %	(IS:2386-Part III, 1963)	36.61	-

Curve plot of particle size distribution of RHA in this study alongside ASTM standard grading requirement for regular sand is shown in Figure 3.11. Sizes corresponding to 60 %, 30 % and 10 % particles finer than, D_{60}, D_{30} and D_{10} and related parameters, coefficient of uniformity C_u and Coefficient of curvature C_c along with fineness modulus FM are also presented at Table 3.9. Based on ASTM guidelines, the coefficient of uniformity C_u value of

3.51 is less than 6 and the coefficient of curvature C_c of 1.21 is between 1 and 3 but near lower limit, suggest that RHA is also poorly graded (ASTM D2487, 2000; Tikalsky et al., 2004). Particle size distribution curve of RHA like SFS is also not between the curves representing upper and lower bounds of well graded sand as per ASTM C33 (ASTM C33/C33M, 2011). This again showed that the RHA also was not well graded. As per particle size distribution, 85% of the RHA particles fall between a size lesser than 0.075 mm (10% quantile) - 0.55 mm (95% quantile). It again means that the grain size distribution of RHA is also skewed towards uniform. Uniform size aggregates are not considered appropriate as fine aggregate in concrete and mortar.

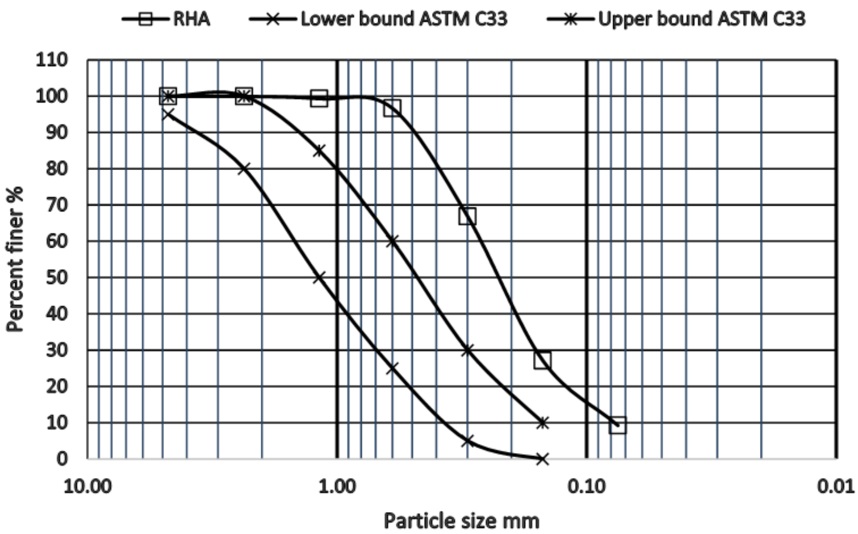


Figure 3.11 Particle size distribution of Rice Husk Ash (RHA)

Fineness modulus (FM) of 1.1 of the RHA in present study is much less compared to range of 2.3-3.1 for normal sand (Bhardwaj and Kumar, 2017). This is reflective of greater fineness of RHA in comparison with natural sand. It is also evident from the fact that there are 9.27 % RHA particles finer than 0.075 mm size which has contributed to fineness of RHA. Notably in case of SFS only 1.02 % particles are finer than 0.075 mm. Parameters D60, D30, and D10, which represent sizes corresponding to 60 %, 30 % and 10 % RHA particles finer than the same, are all lower than that for SFS. This means RHA has more finer particles than SFS. For this fact, it is also considered to be too fine and not considered suitable as replacement of natural sand at higher levels similarly as SFS.

Table 3.9 Particle size related properties of Rice Husk Ash (RHA)

S. No.	Property	Relevant code	Value of present study
1.	Fineness modulus (FM)	(IS:2386-(Part-1), 1963)	1.10
2.	60 % finer than -D_{60} (mm)	(ASTM D2487, 2000)	0.27
3.	30 % finer than -D_{30} (mm)	-do-	0.16
4.	10 % finer than -D_{10} (mm)	-do-	0.08
5.	Coefficient of uniformity $C_u = D_{60} / D_{10}$	-do-	3.51
6.	Coefficient of curvature $C_c = [D_{30} \times D_{30}] / [D_{10} \times D_{60}]$	-do-	1.21
7.	% Finer than 75 µm	-do-	9.27

3.2.5 Water

Water is significant for CLSM as it provides flowability to the mix. Flowability is very important and the foremost property that make CLSM to be self-levelling and fill congested locations. Tap water was used for mixing the CLSM throughout the entire study. ACI 229R (1999) also specifies use of water that is acceptable for concrete to be also suitable for CLSM.

3.3 EXPERIMENTATION METHODOLOGY

The proposed experimentation methodology for the preparation and evaluation of CLSMs mixes is summarized in Fig. 3.12. Methodology involves deciding the mix proportions with desired flowability, testing of the CLSM mixes in fresh/plastic state and hardened state, along with microstructural analysis and mineral phase identification. Also, leachate toxicity examination and ecological analysis have been carried out for final evaluation of the mixes keeping in view the industry accepted parameters.

3.4 CLSM MIXTURES

Two industrial by-products namely spent foundry sand (SFS), cement kiln dust (CKD)and one agro based by-product as rice husk ash (RHA) were considered for evaluating their potential to develop CLSM with acceptable characteristics. In this study, it was proposed to utilize cement and CKD as binders. Other by-product materials, SFS and RHA were taken as fine aggregate or filler. Objective was to maximize use of by-products for sustainability and explore the possibility of development of CLSM entirely by use of by-products. It is notable that conventionally CLSM are comprised of cement, fly ash, natural fine aggregate and water. In present study, SFS and RHA were proposed to be used singly or in combination to completely substitute the natural fine aggregates. Additionally, cement was progressively replaced by CKD to formulate different mixture proportions for testing. The flowability requirement of proposed CLSM mixes was targeted around a range of 200-250 mm flow tested as per ASTM D6103 (ASTM D6103, 2004). CLSM are supposed to have good flowability if the flow spread diameter measured is at least 200 mm, with no segregation (ACI 229R, 1999). A higher flowability above 250 mm could have required addition of more water content in the mix leading to issues of segregation and more bleeding (Han et al., 2023). Flowability of around 200-225 mm has been used in various studies previously also (Do et al., 2019; Naganathan et al., 2012; Nataraja and Nalanda, 2008; Park et al., 2017; Wang et al., 2018). Further, based upon strength, the mixes having 28 days unconfined compressive strength less than 2.1 MPa are categorized as excavatable CLSM and between 2.1 to 8.3 MPa as non-excavatable. Present study also aimed at achieving excavatable CLSM mixes.

The proportioning of the constituents of CLSM mixes is usually finalized by trial and error procedures till achievement of the desired properties e.g. strength, flowability etc. (ACI 229R, 1999; Alizadeh et al., 2014; FHWA, 2016b). Many studies have conducted the research work by choosing some nominal mix proportions and evaluated the performance of the mixes in respect of various CLSM properties for acceptance for an appropriate application (Do et al., 2019; Her-yung, 2009; Hwang et al., 2017; W. Kuo et al., 2013; Nataraja and Nalanda, 2008; Zhen et al., 2013). Evaluation of the trial mixes determines their acceptability in terms of required specifications about unit weight, strength, flowability or any other chosen property. In present study, three combinations of constituents were proposed for CLSM mixes, which are mentioned in Table 3.10 and Figure 3.13.

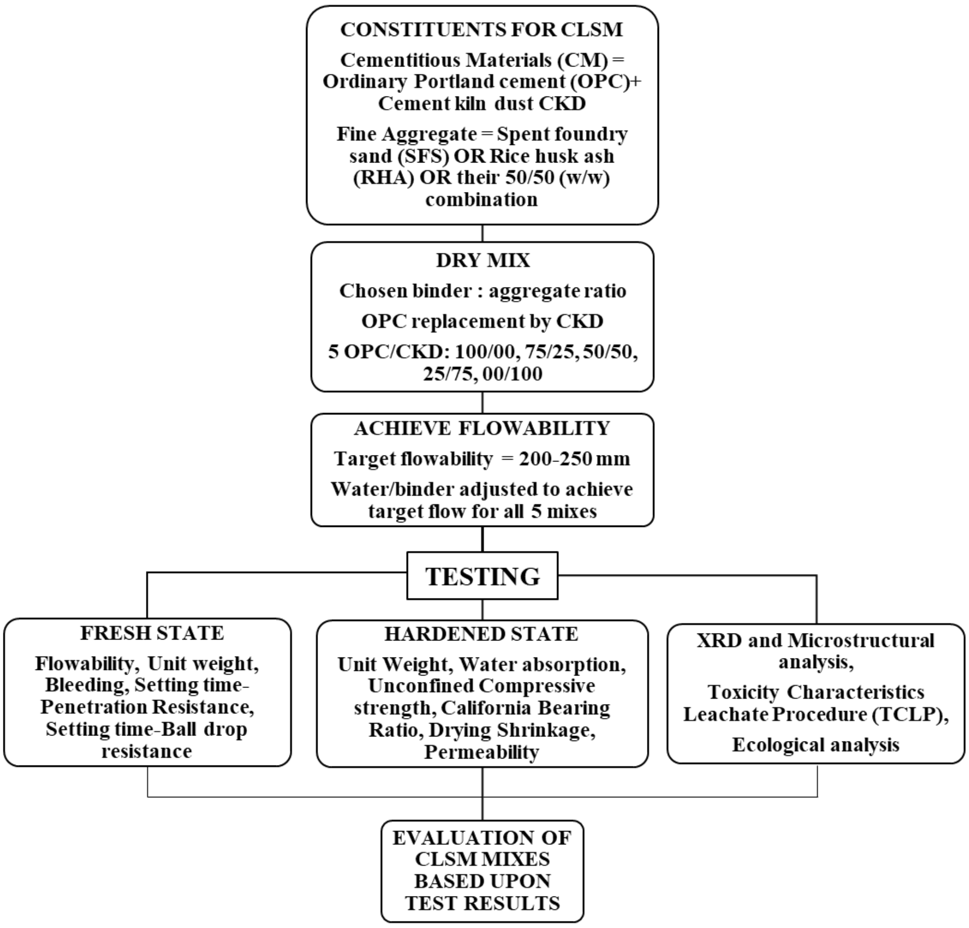


Figure 3.12 Experimentation Methodology

Table 3.10 Constituents grouping for CLSM mixes for experimentation

CLSM mixes	Binder	Fine aggregate
Group-1	Cement and CKD in 5 combinations 100/00, 75/25, 50/50, 25/75 and 00/100 (w/w)	SFS
Group-2	Cement and CKD in 5 combinations 100/00, 75/25, 50/50, 25/75 and 00/100 (w/w)	RHA
Group-3	Cement and CKD in 5 combinations 100/00, 75/25, 50/50, 25/75 and 00/100 (w/w)	SFS+RHA in 50:50 (w/w)

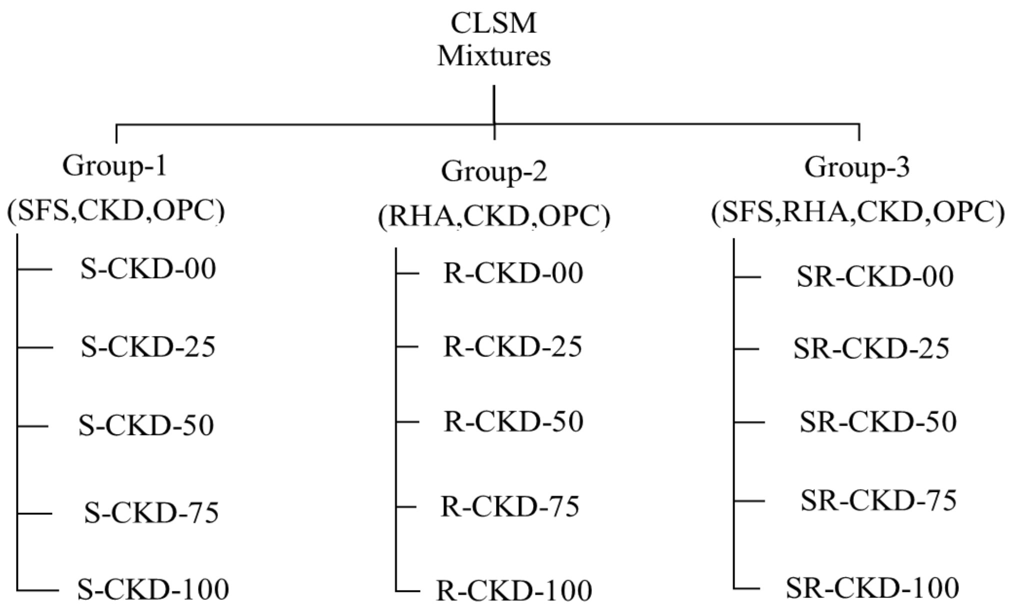


Figure 3.13 CLSM mixtures and their nomenclature

3.4.1 CLSM Group-1 with OPC, CKD and SFS

OPC and CKD both were considered as binder. SFS has been considered as the only fine aggregate. Proportioning of the constituents of CLSM mixes is usually finalized by trial and error procedures till achievement of desired properties e.g. strength, flowability etc. (ACI 229R, 1999; Alizadeh et al., 2014; FHWA, 2016b). In the Group-1, similar type of trial-and-error procedure was adopted. Many previous studies have conducted the research work by choosing some nominal mix proportions and evaluated the performance of the mixes in respect of various CLSM properties for acceptance for an appropriate application (Do et al., 2019; Her-yung, 2009; Hwang et al., 2017; W. Kuo et al., 2013; Nataraja and Nalanda, 2008; Zhen et al., 2013). Further, a typical CLSM has 80-85 % fine aggregate or filler, 10-15 % SCM and 5-10 % cement of the total mass (FHWA, 2016b; Lachemi et al., 2010) with a scope for variation in actual proportioning depending upon possible application.

For the purpose of mix proportioning two previous studies using CKD as binder were referred. Firstly, Lachemi et al., (2010) in a CLSM study with binder (CKD + Slag) to fine aggregate (natural sand) ratios of around 1:2.5 to 1:6 observed a 28 days compressive strength of 1.5-8.11 MPa. The slump flow was 210-245 mm. The mix having maximum aggregate with binder aggregate ratio of 1:6 showed compressive strength of 1.50 MPa. Similarly, in another study Lachemi et al. (2008) used CKD and cement as binders with natural sand as fine aggregate, observed a compressive strength between 1.9-4.0 MPa for binder aggregate ratios of around 1: 0.7 to 9.4. The slump flow was 420-515 mm. Both the studies showed low compressive strength for the poorer binder to aggregate ratios i.e., high aggregate content in comparison to binder.

With the objective of maximum by-product utilization, the higher binder aggregate ratio (1:9.4) was focused on. This was also in the excavatable range with compressive strength < 2.10 MPa. The proportions and characteristics of constituents had influenced the result. It was also notable that unlike natural sand as fine aggregate in above studies, spent foundry sand was the only fine aggregate chosen in the Group-1 study. Group-1 study also aimed to develop excavatable CLSM mixes and therefore a binder to aggregate ratio as 1:10 by weight was chosen for experimentation in this study. By this, binder worked out as 6.8 % of the total constituents including water was within the recommended level 5-10 % in literature (FHWA, 2016b; Lachemi et al., 2010). Further the cement and CKD proportioning was also varied in the binder combination with progressively adding CKD by 25 % as replacement of cement at each level. This resulted into five Cement/CKD mix combinations as 100/00, 75/25, 50/50, 25/75 and 00/100. CLSM are supposed to have good flowability if the flow spread diameter measured as per ASTM D6103 (2004) is at least 200 mm, with no segregation. Water content has been decided by flowability test (ASTM D6103, 2004) for a target flow of around 250 mm. The mix proportioning for CLSM group-1 constituents is presented at Table 3.11.

Table 3.11 Mix proportions for CLSM mixes Group-1 with OPC, CKD, SFS

Mix designation	Cement / CKD	Cement kg/m^3	CKD kg/m^3	SFS kg/ m^3	Water kg/m^3	water to binder w/b	Binder to aggregate ratio
S-CKD-00	100/00	126	0	1255	471	3.76	1:10
S-CKD-25	75/25	94	31	1250	470	3.76	1:10
S-CKD-50	50/50	63	63	1263	463	3.67	1:10
S-CKD-75	25/75	31	94	1250	459	3.67	1:10
S-CKD-100	00/100	0	127	1272	452	3.56	1:10

3.4.2 CLSM Group-2 with OPC, CKD and RHA

In this set of proposed CLSM mixes, again OPC and CKD both were considered as binder. RHA has been considered as the only fine aggregate or filler. RHA in as received and unprocessed condition was proposed to be used as fine aggregate substitute. For trial-and-error process nominal mixes with cement, RHA ratios 1:6, 1:4 and 1:3 were chosen for evaluation. Flowability and compressive strength were the evaluation criteria, which are very important parameters regarding placement and performance for a functional CLSM. The cement: RHA

1:3 mix was found suitable with reasonable 28 days unconfined compressive strength of around 0.30 MPa and flowability of around 220 mm. Notably compressive strength of 0.21MPa is reported to be equivalent to bearing capacity of well compacted soil (Alizadeh, 2019). Other mixes due to low cement were faced with issues of segregation and low strength. Further, It is mentioned that there is only one study available in literature about use of both cement and RHA in CLSM (Nataraja and Nalanda, 2008), which used RHA as fine aggregate with three nominal cement to RHA ratios of 1:17.5, 1:10 and 1:5 and used pulverized RHA in the study and 28 days strength of 0.176, 0.281 and 0.487 MPa respectively was observed. The said study used pulverized RHA. However, in the Group-2 study, the unprocessed and as received RHA has been proposed to be used as the fine aggregate. Further, the cement was also proposed to be progressively replaced with CKD up to 100 %. Keeping the above changes in both the binder and aggregate, a richer nominal mix of binder/aggregate as 1:3 was chosen for further experimentation in Group-2 study. The cement and CKD proportioning was varied with 25 % addition of CKD as replacement of cement at each level to have five Cement/CKD mix combinations as 100/00, 75/25, 50/50, 25/75 and 00/100 to be tested. A constant water/cement ratio for all the mixes was arrived at through flowability testing as per ASTM D6103 (2004) to achieve a target flow of between 200-250 mm. The constituents' proportioning for CLSM mixes in Group-2 are presented at Table 3.12.

Table 3.12 Mix proportions for CLSM mixes Group-2 with OPC, CKD, RHA

Mix Designation	Cement / CKD	Cement kg/m^3	CKD kg/m^3	RHA kg/m^3	Water kg/m^3	Water to binder (w/b)	Binder to aggregate ratio
R-CKD-00	100/00	101.4	0.0	304.0	836.4	8.25	1:3
R-CKD-25	75/25	75.9	25.3	304.0	835.1	8.25	1:3
R-CKD-50	50/50	50.3	50.3	302.0	830.2	8.25	1:3
R-CKD-75	25/75	25.1	75.3	301.0	828.4	8.25	1:3
R-CKD-100	00/100	0.0	100.0	300.0	824.8	8.25	1:3

3.4.3 CLSM Group-3 with OPC, CKD, SFS and RHA

In this set of proposed CLSM mixes, again OPC and CKD both were considered as binder. SFS and RHA combined in 50:50 ratio by weight have been considered as the fine aggregate or filler. Proportioning was done with a same nominal ratio of binder to aggregate as 1:3 by weight as in the case of Group-2 mixes. The cement and CKD proportioning was also similarly varied in the binder combination with 25 % addition of CKD by replacing cement.

Five cement/CKD mix combinations as 100/00, 75/25, 50/50, 25/75 and 00/100 were proposed to be tested. However, the water content for each mix was determined for the target flowability of 200 mm through flowability testing as per ASTM D6103 (2004). This was less in comparison to Group-1 and 2 and expected to result into lesser setting times. The constituents' proportioning in CLSM mixes in Group-3 are presented at Table 3.13.

Table 3.13 Mix proportions for CLSM mixes Group-3 with OPC, CKD, SFS and RHA

Mix Designation	Cement / CKD	Cement kg/m^3	CKD kg/m^3	SFS kg/m^3	RHA kg/m^3	Water kg/m^3	Water to binder (w/b)	Binder to aggregate ratio
SR-CKD-00	100/00	168.3	0.0	252.4	252.4	739.1	4.39	1:3
SR-CKD-25	75/25	124.2	41.4	248.4	248.4	739.2	4.46	1:3
SR-CKD-50	50/50	82.2	82.2	246.6	246.6	739.8	4.50	1:3
SR-CKD-75	25/75	40.6	121.7	243.4	243.4	741.7	4.57	1:3
SR-CKD-100	00/100	0.0	187.5	281.2	281.2	696.4	3.71	1:3

3.5 MIXING

Mixing the constituents in concrete, mortar or CLSM is supposed to uniformly blend all the materials to achieve homogeneity, consistency and make it ready for placement at the desired location. The paste volume, quantity and various characteristics of the constituents, like grading, fineness, particle shape (sphericity) etc. are supposed to effect on the mixing process (Westerholm et al., 2008). In all the groups of CLSM mixing procedure started with batching of the dry constituents by weighing. The batched materials were dry mixed manually till homogeneous mix is achieved and then put into mixing bucket. Required water content is added intermittently and mixing is done till the entire water gets added and the mixture of desired homogeneity is obtained. An electrically operated mortar mixer was employed for mixing the CLSM constituents.

3.6 TESTING

Evaluation of proposed CLSM mixes was done on the basis of various technical parameters or characteristics considered as desirable attributes for a CLSM's application as backfill. Various tests for ascertaining the characteristics of each proposed CLSM mix in fresh/plastic and hardened state were conducted. The details of the same along with relevant standard, specimen size and age at which test was conducted are presented in Table 3.14. Details of the various test procedures for the evaluating characteristics of proposed CLSM in fresh and hardened state are discussed in the following sections.

Table 3.14 Properties of CLSMs, relevant standard, specimen size and age for testing

1.	**Fresh/ Plastic state**	**Specimen size**	**Age for testing**	**Relevant standard**
i	Slump flow	75-ϕ ×150 mm	Fresh	(ASTM D6103, 2004)
ii	Unit weight	1.5 litre	Fresh	(ASTM D6023, 2015)
iii	Bleeding and subsidence	1-litre	Fresh	(ASTM C940, 2003)
iv	Initial setting time (Penetration resistance)	150-ϕ ×150 mm	Varying	(ASTM C403, 2008)
v	Setting time / Loading time (Ball drop resistance)	400 × 400 × 15 mm	Varying	(ASTM D6024, 2016)
2.	**Hardened state**			
i	Unit weight, Water Absorption	Broken pieces of 28-days cylinders	28 days	(ASTM C642, 2013)
ii	Unconfined compressive strength	100-ϕ × 200 mm	Till 90 days	(ASTM D4832, 2010)
iii	California Bearing ratio	150-ϕ ×	At time of ≤ 76 mm ball indentation.	(IS 2720 (Part-16), 1987)
iv	Drying shrinkage	75 × 75 × 285 mm	Till no shrinkage.	(ASTM C596, 2015)
v	Permeability	100-ϕ × 100 mm	28 days	(IS:3085, 1965)
vi	Toxicity characteristics leachate procedure (TCLP)	Broken pieces of 28 days cylinder	28 days	(USEPA-1311, 1992)
3 (i)	Mineral phase identification	Broken pieces of 28 days cylinder	28 days	X-ray diffraction (XRD)
3 (ii)	Microstructural analysis	Broken pieces of 28 days cylinder	28 days	FE-SEM*, EDS*
4.	Ecological analysis	-	-	EE** and ECO_2**

**FE-SEM is Field emission scanning electron microscopy; EDS is Energy dispersive spectroscopy*

***EE is Embodied energy; ECO_2 is embodied carbon dioxide*

3.6.1 Flowability

Flowability is the most important characteristic of CLSM that separates it from a normal fill material. It facilitates self-levelling of the flowable mix, placing in to congested sites and self-compacting. CLSM are advantageous over conventional fills that need mechanical placing and compaction. Flowability is a measure of workability and variations from stiff to fluid are possible depending upon requirements. As per ACI 229R (1999) flowability of CLSMs can be measured by using 75 × 150 mm tube, normal slump cone or flow cone. In present study, tube flow test was conducted as per ASTM D6103 (2004). In this procedure, open-ended cylinder of 75×150 mm size was placed on a flat non-absorbent surface and held firmly. Fresh CLSM after mixing was poured in the cylinder from top open end quickly. The top surface of the cylinder filled with CLSM is struck off with straight edge to flush the level with the brim of top end of the tube. The cylinder filled with the freshly prepared mix was lifted vertically. The CLSM grout flows and spreads over the flat surface in pan-cake patty shape. The diameter of the pan-cake patty of CLSM was measured in two perpendicular directions and mean of the two observations was recorded as the flowability of the mix. According to this method, if the CLSM pan-cake patty diameter is equal to or more than 200 mm without any noticeable segregation and bleeding, the good flowability is supposed to have been achieved (ACI 229R, 1999). The typical flowability measurement is as shown in Figure 3.14.

Figure 3.14 Flowability test

3.6.2 Fresh state unit weight

Unit weight in fresh state of CLSM is significant in terms of the loading it causes upon embedded utility elements like pipes which need to strong enough to resist such loads. Liquid CLSM can even cause floatation of the underground pipes, tanks and cables (ASTM D6023, 2015). Similarly, liquid state CLSM also can exert lateral pressure upon shoring, basement walls and other structures till it hardens. Notably, lateral pressure is directly related to unit weight of the liquid material. Unit weight of the fresh CLSM was measured as per procedure mentioned in ASTM D6023 (2015). Metal container of about 1.5 litre volume was filled with fresh CLSM mix. The surplus CLSM material was struck off with a straight edge to make the CLSM surface flush with the top edge of the container. Weight of the CLSM is calculated as difference of full and empty container. Volume of the container was determined by filling it with water and weighing. The fresh unit weight is calculated by dividing the net weight of CLSM in a container by its volume. Mean of the two test observations was recorded as unit weight in fresh state.

3.6.3 Bleeding / subsidence

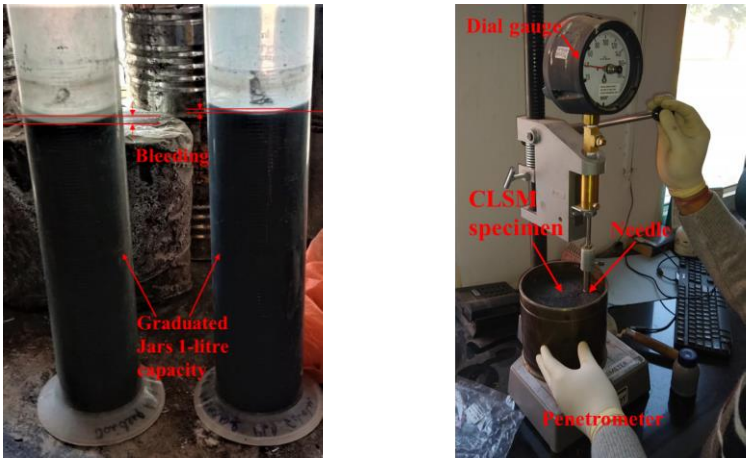
Bleeding is the release of surplus mixing water over the surface of grout with time which also causes contents to settle or subside. As per ACI 229R (1999) the water added to create flowability, when more than that required for hydration, is either absorbed in the adjoining soil mass or expelled to the surface as bleeding water. Most subsidence of CLSM occurs during its placement and its extent varies with the quantum of surplus water expelled. High flowability requirement of a CLSM requires high water content which might result in segregation, bleeding and also delayed setting/hardening of the mix (Kaliyavaradhan et al., 2019). Also based upon the surrounding soil character, absorption of water by soil can influence strength of the CLSM (Folliard et al., 2003). Absorption of water into the surrounding soil is also reported to cause subsidence throughout the depth of the fill (Shon et al., 2010) and delayed setting (Katz and Kovler, 2004).

Bleeding of the mixes has been checked in accordance with the ASTM C940 (2003). In this procedure, about 800 ml fresh CLSM mix was poured into a graduated jar of around 1 litre capacity. The jar was placed upon horizontal surface which is vibration free. The initial observation about the volume of grout was noted corresponding to the graduation marking for its top surface. The jar was covered to prevent any evaporation of water. The readings for bleeding were taken by recording measurements of grout top and the top of water surface at regular intervals of time. Final readings were taken when there was no difference between the two reading for the top surface of grout. Finally, the bleed water that appeared on the top of grout surface was withdrawn by dropper and measured. Bleeding was calculated as the volume of bleed water as percentage of the total volume of the CLSM grout initially taken. Mean of the measurements from two specimen was taken as final bleeding of the CLSM mix. Naganathan et al. (2012) have also worked out stability as bleeding in the same manner. It has been also stated that CLSM with stability up to 5% at 2 hours can be considered stable. The apparatus and the ongoing test for evaluation of bleeding in present study is shown in Figure 3.15 (a).

3.6.4 Setting time (Penetration Resistance-PR)

A CLSM need to be sufficiently stiff before being put in to service. As CLSM are primarily used as backfill, these should have attained sufficient bearing strength so that these can be subjected to the desired loadings. Time from the addition of water to the attainment of desired stiffness termed as setting time is considered as an important parameter for characterisation of CLSMs.

Setting time of the CLSM mixes was examined as per (ASTM C403, 2008). In this procedure the fresh CLSM mix was poured for a depth of about 150 mm in to a cylindrical mild steel mould having about 150 mm diameter. The CLSM specimen with the mould was kept at room temperature for curing in air. A penetrometer equipment was used to apply controlled loading to penetrate the standard needle by 25 mm into the surface of stiffening CLSM specimen in the mould. The resistance offered, in terms of load, to the penetration of the standard needle and the time from addition of water till the testing age was recorded. Penetration resistance was measured using a standard needle from the set of needles with 323 mm^2, 161 mm^2, 65 mm^2, 32 mm^2 and 16 mm^2 tip sizes, which depended upon the stiffness attained by CLSM at that moment. Choice of needle was guided by the need to obtain a successful record of penetration resistance by the equipment within its limitations. As a general guide harder the CLSM, smaller needles were appropriate to give a reading and vice versa. The needles were penetrated in the circular region on the CLSM surface with a boundary at least 25 mm inside the wall of cylindrical specimen. Additionally, a distance of twice the diameter of larger needle was maintained between two penetrations to avoid any already disturbed portion. The penetration test was conducted at shorter intervals in the beginning because of higher rate of strength gain initially. However, with the passage of time the penetration testing intervals were increased as the strength gain decreased. The force required for the penetration was divided by the bearing area to obtain penetration resistance of the mix. Capacity of the penetration resistance equipment or penetrometer was 200 lbs (889.6 N) and a least count of 2 lbs (8.9 N).



(a) (b)

Figure 3.15 Fresh state tests (a) Bleeding test (b) Setting Time test as per penetration resistance

Penetration resistance (PR) of CLSM at two levels i.e., 0.344 MPa and 2.76 MPa is important (Naganathan et al., 2012; Tikalsky et al., 2004). The time duration taken to achieve a PR of 0.344 MPa, which is appropriate for supporting human foot traffic and further loading without noticeable subsidence, is termed as the initial setting time. And the time duration for PR of 2.76 MPa, which is threshold for vehicular loads, as the final setting time. Graphs between recorded penetration resistance and the corresponding time for a CLSM mix and time against the desired PR of 0.344 MPa and 2.76 MPa were worked out as initial and final setting time. Mean of the observations from two specimen was considered. The penetration resistance testing by the penetrometer is as shown in Figure 3.15 (b). Typical penetration resistance versus time plot showing achieved initial setting time for PR=0.344 MPa and final setting level for PR=2.76 MPa is presented in Figure 3.16.

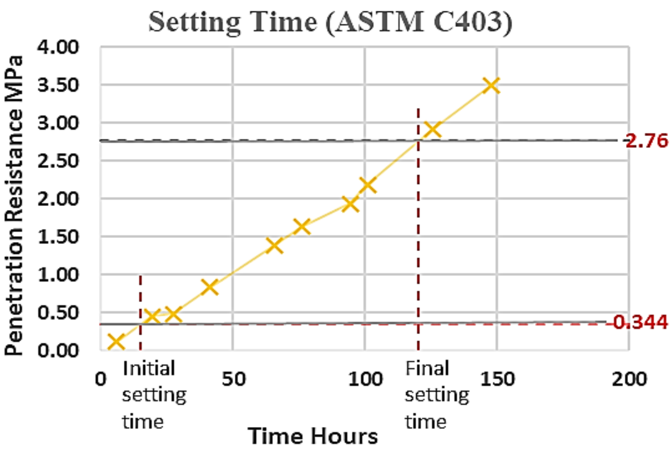


Figure 3.16 Setting time as per Penetration Resistance vs Time (Typical)

3.6.5 Setting time (Ball drop resistance)

Degree of hardening of CLSM mixes was also examined through load application suitability by conducting a ball drop resistance test as per (ASTM D6024, 2016). In this test a sheet metal mould of rectangular shape with size 400 × 400 × 150 mm was used as suggested in literature (Lachemi et al., 2008). The fresh CLSM was placed in the mould which was left undisturbed and kept at room temperature for curing. Any bleed water was removed initially while putting the specimen for curing and before conducting the ball drop testing. The specimen gains strength and stiffness with time. At the time of test, a hemispherical metal ball having around 150 mm diameter and weighing between 14-15 kg was dropped through a fall of 108-114 mm for five times on the surface of the hardening CLSM specimen. Thereafter, diameter of indentation made by the ball over the CLSM surface is measured with a scale.

The CLSM is considered to have achieved the loading suitability when the diameter of indentation is equal to or less than 76 mm. The time corresponding to the 76 mm indentation has been considered as ball drop setting time. It is also notable that as per ASTM D6024 (2016), the stiffness level for a 76 mm indentation is appropriate for backfill application in utility trenches. Additionally, indentation diameter of 100 mm has also been termed as acceptable in pavement subgrade. The data regarding the time elapsed and the corresponding indentation was plotted and the time for 76 mm indentation was worked out. The testing with ball drop apparatus is shown in Figure 3.17. Typical graph plots between indentation diameter versus time along with time recorded for achievement of 76 mm indentation is shown in Figure 3.18.

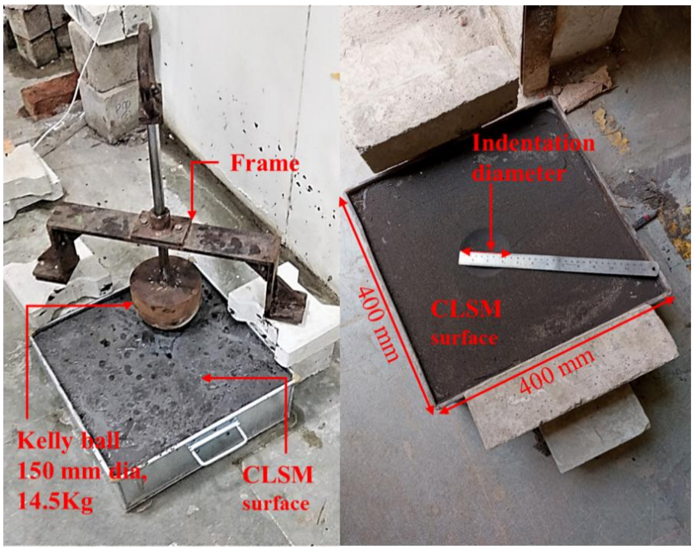


Figure 3.17 Setting time test as per Ball drop resistance and indentation measurement

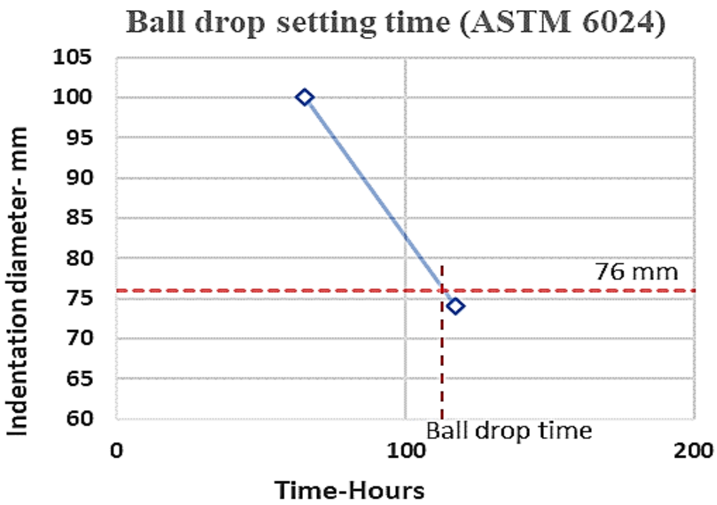


Figure 3.18 Setting time as per Ball drop indentation vs time plot (Typical)

3.6.6 Hardened state Unit weight

Unit weight of the hardened CLSM samples was evaluated in as unmoulded (AU) and in oven dried (OD) condition as per ASTM C642 (2013). For this the broken pieces of specimens that remained after testing the unconfined compressive strength of the CLSM at 28 days were used. It was ensured that the chosen pieces for test were free from observable cracks. The process involved determination of weight and the volume of the specimen. The broken pieces of CLSM were weighed in as unmoulded (AU) condition. Then these pieces were put in oven for drying at 110^{o} C for 24 hours and their weight was checked. It was ensured that drying of moisture was complete, for which specimens were dried till no change is observed between two successive weight measurements. This was recorded as oven dried (OD) weight of the specimens. These oven dried pieces were then immersed in water for 24 hours and again weighed. Further, their submerged weight is recorded. Difference of the specimen weight after absorption for 24 hours and its weight in submerged condition gave the volume of respective specimen. The unit weight was calculated by dividing the observed weight of a specimen in AU or OD condition by its volume as ascertained above. Finding the unit weight of the specimen with 100 % CKD as binder by above procedure was not possible as the specimen crumbled when immersed to ascertain volume. However, unit weight in AU were worked out by weighing the cylindrical specimen before compressive strength testing and with dimensions measured for calculating the volume. However, the OD weight of the cylinder was deduced by using weight in oven dried condition and as unmoulded state of broken specimen pieces obtained after compressive strength test. Water absorption potential was also calculated from the difference between the weight of a saturated specimen (after 24 hours immersion) and the OD specimen. Water absorption potential for specimen with 100 % CKD as binder could not be ascertained as the specimen crumbled when immersed due to inadequate binding between constituents.

3.6.7 Unconfined compressive strength (UCCS)

As CLSM is adopted for different applications with the requirement of different bearing capacities. While it is important to visualize the possible loads to be imposed over CLSM, it is equally important to know bearing capacity also. Unconfined compressive strength is a defining parameter for the load bearing capacity of a CLSM. It is also used for defining the future excavatability of the CLSM as the CLSM with UCCS less than 2.1 MPa is considered excavatable as ACI 229R (1999). Notably, a backfill may require to be excavated in future to facilitate repairs and maintenance of the embedded utility elements like pipeline or cable etc. Unconfined compressive strength test is the most common method among many for measuring the strength of CLSM. Unconfined compressive strength (UCCS) testing was conducted as per ASTM D4832 (2010).

The UCCS test was conducted on specimen of 100 × 200 mm size at curing ages of 28 days, 56 days and 91 days. For preparation of the CLSM specimen, PVC pipe moulds of 100 × 200 mm size were prepared. Specimen under curing, demoulded specimens and UCCS testing are depicted in Figure 3.19.

Keeping in view the fragility of CLSM due to low strength, the specimen needed to be handled with care during demoulding for testing. Therefore, cylindrical mould were split along length and secured by tape to maintain shape (Du et al., 2002) which was gently removable for facilitating easy demoulding. For casting the specimens, the fresh CLSM was poured into the cylindrical moulds which were left for curing without any tamping or compaction etc. For every curing age three specimens were cast. The cylindrical specimens were cured at ambient temperature as suggested in literature (Ho et al., 2022; Hwang et al., 2017) till the testing age. Also curing was done in the mould itself until testing (Ahadzadeh Ghanad and Soliman, 2021; Folliard et al., 2003; Mneina et al., 2018; Tikalsky et al., 2000). In-mould curing was adopted in order to make it more relatable to actual situations (trench filling/backfilling) as CLSM is supposed to be covered on sides but exposed on top. The unconfined compressive strength test was conducted on the triaxial loading equipment having 15 kN capacity and a least count of 15 N. At the time of testing, every care was taken to demould the specimen unharmed by cutting the tape along the length and at the bottom. After seating the demoulded specimen in desired position on the loading equipment, the load was applied at a strain rate of 1.2 mm/min. With increasing strain, increasing load represented by forward movement of needle was monitored until the needle on dial gauge reverses after touching the ultimate load point. Mean of the three specimen was taken as the unconfined compressive strength.

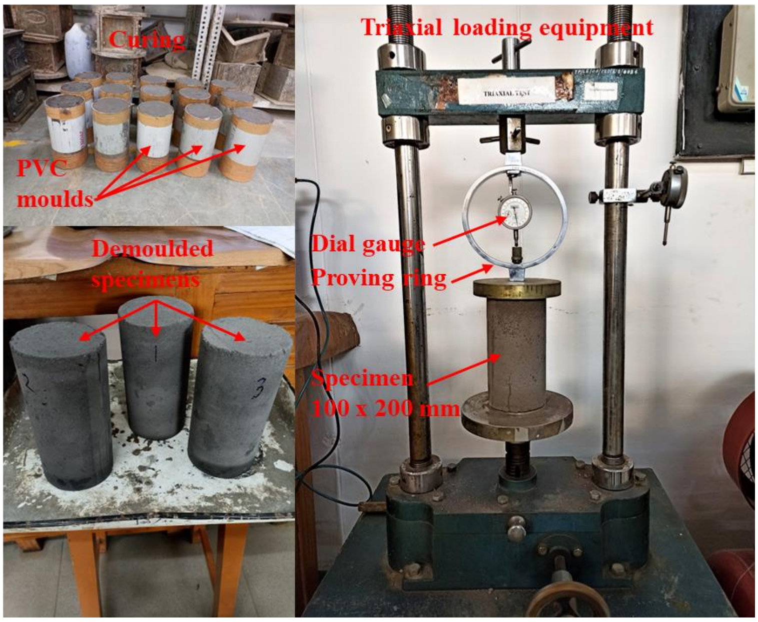


Figure 3.19 Unconfined compressive strength test

3.6.8 Drying shrinkage

Shrinkage has been known to take place in the initial setting period after evaporation of the bleeding water (Thaha, 2007). However, the shrinkage growth after the hardening of the mix gets reduced very much and not remains a concern. It is therefore a function of reduction of moisture from the hardening mix. Loss of moisture may be associated with loss to ambient environment, cement hydration and pozzolanic activity in the mix. Shrinkage may result into cracks in CLSMs due to typically more water cement ratio necessitated for flowability as well as consequential low strength-gain. Drying shrinkage of the CLSM was tested as per ASTM C596 (2015) specimen with prismatic specimens of 75 × 75 × 285 mm size. Fresh CLSM mix was poured in to the mould for casting the specimens for drying shrinkage. Three specimens were cast for every CLSM mix. The specimens were stored for air drying at 23 ± 2°C and 50 ± 4% relative humidity. Specimens were demoulded after 4 days of casting and initial comparator reading was taken with the help of a length comparator which had a range of 0.01-25 mm for recording change in length measurements. Cast specimens, drying process and measurement of the length change with comparator are as shown in Figure 3.20. Further observations were recorded weekly from day 4 i.e., at 11th, 18^{th} and 25^{th} day from casting and later at a gap of 28 days from 25^{th} day onwards till achieving the ultimate drying shrinkage e.g. after 53, 81, 109 days and so on, to track change in length. In case of group-1 constituents i.e., OPC, CKD and SFS, the shrinkage testing of only four mixes could be performed as the specimens with 100% CKD crumbled while demoulding due to very low strength achieved.

Figure 3.20 Drying shrinkage test

3.6.9 California bearing ratio (CBR)

California bearing ratio is standard test conducted for assessing the bearing capacity of the CLSM. CBR testing was done in accordance with the procedure specified by IS 2720 (Part-16), (1987) or the equivalent standard (ASTM D1883, 2009). CLSM specimens were with fresh mix cast in metal cylindrical moulds sized about 155 mm and 175 mm high. The specimen were left for normal curing till the age of ball drop setting time corresponding to 76 mm indentation as suggested in literature (Lachemi et al., 2008). The testing involves penetration of a plunger of 50 mm diameter in to the hardened surface of CLSM and recording the resisted load along with the corresponding penetration. The CBR equipment used for conducting the testing had a 50 kN capacity and strain rate of 1.25 mm/min. The process of evaluation of load for penetration of standard plunger in the CLSM specimen with the CBR equipment is shown in Figure 3.21. During the application of strain loading, different load values corresponding to penetrations of 0.5, 1.0, 1.5, 2.0, 2.5, 4.0, 5.0, 7.5, 10.0, and 12.5 mm were recorded. Further the load vs penetration curves were plotted with application of any correction for upward concavity. In case of correction to the load penetration plot, the load values for corrected positions of penetrations are to be taken for calculations. CBR values are percentage of the observed load for penetration of 2.5 or 5.0 mm with the respective standard value of 1370 kg and 2055 kg. Higher of the two values thus obtained is considered as the CBR value of the tested CLSM.

Figure 3.21 CBR test

3.6.10 Permeability

Permeability is also known as hydraulic conductivity of the hardened specimen of a CLSM mix. Permeability of the CLSM mixes was examined at constant head as per IS:3085 (1965). Cylindrical specimens of size 100 × 100 mm and cured for 28 days were used in this test. CLSM specimens were saturated in water prior to packing them in the permeability cell for expediting the process (Lachemi et al., 2008, 2007; Thaha, 2007). Effective sealing around the specimen was ensured by use of silicone gel sealant. The permeability set up was made using 100 mm diameter PVC pipe as water reservoir and permeability cell was also made by splitting PVC pipe which was secured by tape to maintain shape. Constant head of water was maintained by continuous supply of water at the upper end of pipe reservoir. Permeability testing with test set up is shown in Figure 3.22.

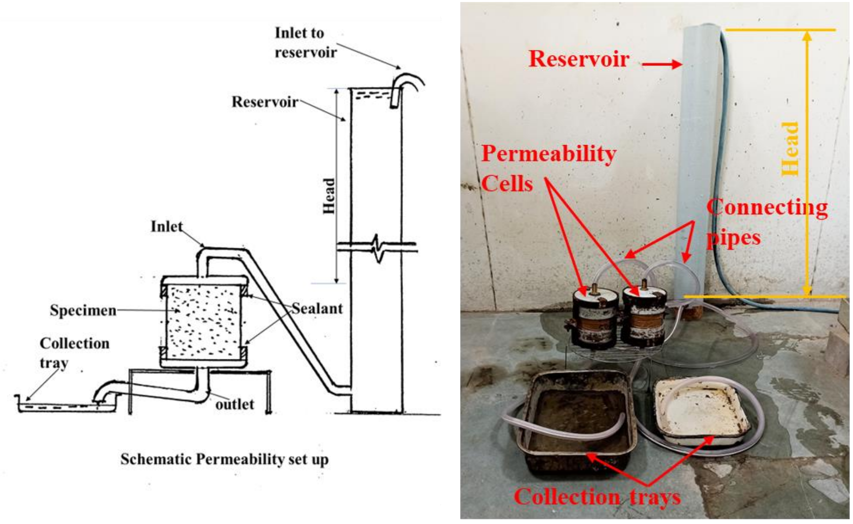


Figure 3.22 Permeability test

The permeability cell with specimen were subjected to supply of water under constant head. The water passing through the specimen as collected from outlet of the specimen cell was continuously monitored till the discharge stabilized or reached a steady state. Then measurements of the quantity of water percolating out of the specimen through the permeability cell outlet were recorded after reasonable time intervals. For specimen with high porosity readings were needed to be taken in quick succession. The above process for a CLSM mix was executed for duration of about 5-6 hours. The total quantity of the water collected and the corresponding time period for each mix were worked out. Permeability was calculated in terms of coefficient of permeability 'K' as per the equation, $K = Q / \{A \times T \times (H / L)\}$, where Q is the quantity of water collected over a time interval T, A is the surface area of the specimen, H is the head and L is the specimen length, both in same length units. Mean of permeability of the two specimens for each mix has been considered as the representative permeability. Permeability testing for mix with 100% CKD as binder was not possible as due to insufficient binding whereupon the specimen could not retain its form when immersed for saturation.

3.6.11 Toxicity examination

The CLSM are primarily used for backfill applications at different situations. Due to the exposure of backfills to weathering phenomena, chances of leaching of harmful compounds into the surrounding soil mass is a realty. Since industrial by-products were being used as input materials for the CLSM mixes in present study, possibility of the existence of heavy metals in the CLSM mixes was required to be ruled out. Leachate toxicity examination is done to ensure that CLSM mix used as backfill is safe in respect of heavy metal concentrations in the leachate that can potentially contaminate the underground water in case the leachate reached that level. Groundwater polluted by leachate can cause aquagenic diseases if consumed through drinking or bathing. Leachate can negatively impact soil's physical, chemical, and biological properties.

Toxicity characteristic leachate procedure (TCLP) of the U.S. Environment Protection Agency as per guidelines provided in USEPA-1311, (1992) was conducted upon the broken pieces of specimens of CLSM, obtained after compressive strength test, to ascertain the environmental impact regarding risk of toxic elements leaching into the surrounding strata. The leachate extraction was done using TCLP extractor for rotating the mixture of 25 gm sample and 250 ml of the extraction liquid for 18±2 hours. The extracted leachate is filtered and concentration of heavy metals are examined by using microwave plasma atomic emission spectrophotometer (MP-AES).

Concentration of the heavy metals namely lead (Pb), cadmium (Cd), copper (Cu), Chromium (Cr), zinc (Zn), nickel (Ni), barium (Ba), lithium (Li), strontium (Sr) and magnesium (Mg) in the leachate of CLSM was examined. The concentrations of the heavy metals in the CLSM mixes were compared with the parametric values, as mentioned in Table 3.15, for ensuring environmental safety. Parametric values for lead (Pb), cadmium (Cd), Chromium (Cr), and barium (Ba) are as per limits for hazardous waste specified by US Code of Federal Regulations CFR-2021 (2021). For other metals such as copper (Cu), zinc (Zn), nickel (Ni) and strontium (Sr), which are not in the above list, a value equivalent to 100 times the levels of USEPA document EPA 822-F-18-001 (2018) and for magnesium (Mg), the level specified in IS: 10500 (2012) have been considered. 100 times the concentration limits of toxic metal for drinking water have been considered as Toxicity Standard presuming that 100 times dilution would occur before the leachate could reach drinking water (Patel and Pandey, 2012; Tikalsky et al., 1998; Wartman et al., 2004).

Table 3.15 Parametric levels of heavy metals as reference

Heavy metal	Pb	Cd	Cu	Cr	Zn	Ni	Ba	Li	Sr	Mg
Parametric value (mg/L)	5	1	130	5	500	70	100	-	2000	3000

3.6.12 Mineral phase identification (XRD)

The X-ray diffraction technique was employed for scanning the CLSM for identification of mineral phases developed in hardened CLSM mixes at 28 days of curing. The X-ray scan was conducted on SmartLab Rigaku made ‘SmartLab SE’ X-ray diffractometer with

Cu-anode for a 2θ range of 10–90° with a step size of 0.01°. Powdered samples for the above were tested for which broken pieces of the 28 days CLSM specimens obtained after compressive strength testing were used. Further analysis of the X-ray diffraction data was evaluated by means of X'pert Highscore Plus software for mineral phase identification. The XRD curves showed sharp and broad peaks, which respectively represented the presence of crystalized and amorphous phases of minerals in the scanned material.

3.6.13 Microstructural analysis (FE-SEM and EDS)

Microstructural examination with field emission scanning electron microscopy (FE-SEM), energy dispersive X-ray spectroscopy (EDS) upon the 28 days hardened CLSM was also done. A Carl-Zeiss Sigma 500 FEG-SEM equipped with Gemini 1 column was used for conducting the microstructure examination and Bruker EDS was used for identification of elemental composition that had developed in the hardened CLSM mix. Broken pieces of CLSM specimen after the unconfined compressive strength testing were used, which were placed upon a special tray with the help of a double-sided conductive tape before being gold (Au) coated. The tray with gold coated specimens was then used for FE-SEM imaging and EDS analysis. The different phases in the FE-SEM images were then compared with morphology of conventional hydration products for identification. Different phases of hydration products were identified by examining similarity with the corresponding microstructure published in previous studies (Barreto and Brandão, 2014; Bouzalakos et al., 2008). Filamentous structure crystals are usually identified as CSH, plate like and hexagonal crystals as calcium hydroxide or portlandite, acicular or needle-like crystal as ettringite and grainy euhedral structure as calcite. Further, additional literature (Nazeer et al., 2023a, 2023b) for identification of microstructure was helpful in this regard. Appropriate inferences were drawn in relation to the differentiation between imaging of different CLSM mixes and their constituent proportioning. EDS analysis was also done to find the elemental composition of a specific phase in the SEM image.

3.6.14 Ecological analysis

Ecological analysis in terms of embodied energy (EE) and embodied carbon (ECO_2) of the CLSM has also been studied. EE is the total energy used for direct, indirect processes within the domain of cradle-to-gate for making the product ready to leave the final factory gate (Hammond and Jones, 2011). It includes processes like extraction of input materials, manufacturing, logistics and fabrication etc. Similarly, ECO_2 is the carbon dioxide emissions related to fuel and process involved for the readiness of product. Total EE and ECO_2 for a mix was calculated as the product of the quantity of each constituent per unit volume of CLSM with its respective coefficient for EE and ECO_2 (Gupta et al., 2019; Hammond and Jones, 2011). Since the industrial by-products were not intentionally manufactured, their EE and ECO_2 coefficients were considered as zero as suggested in literature (Chompoorat et al., 2021; Gupta et al., 2019). Comparison of CLSM and the conventional backfill in terms of EE and ECO_2 was also evaluated. Ecological analysis of different CLSM mixes facilitated assessment of the impact of variation of mix proportions upon the EE and ECO_2.

Suitability of developed CLSM mixes for construction applications was ascertained by comparing the characteristics with the relevant industry standard and reasonability.

Chapter 4

RESULTS AND DISCUSSION

4.1 GENERAL

The objective of the present study was to evaluate the utilization potential of industrial by-products and hazardous waste materials for developing CLSM, investigating their engineering properties in fresh and hardened state, using these wastes either as cement or fine aggregate replacement and along with investigating the leachability of the mixes for ascertaining safety aspect of using such materials for various application. Results of the testing program outlined in chapter 3 for this study have been provided in this section. Also detailed discussions are based upon the testing results of the different CLSM mixes proposed for evaluation in this study and the previous research. With by-products namely CKD, SFS and RHA along with cement as constituent materials, three test groupings were formulated as (i) cement, CKD as binder and SFS as fine aggregate (ii) Cement, CKD as binder and RHA as fine aggregate and (iii) Cement, CKD as binder and SFS plus RHA as fine aggregate, for the development of CLSM for evaluation. Mix proportions for the above groupings listed at section 3.4.1, 3.4.2 and 3.4.3 were tested for various properties and the findings are given in the following sections.

4.2 PROPERTIES OF THE GROUP-1 CLSM MIXES *(Cement + Cement Kiln Dust binders and Spent Foundry Sand as fine aggregate)*

Five mix proportions were chosen for experimentation in order to maximize use of industrial by-products by increasing the replacement of OPC with CKD. Considering binder to aggregate ratio as 1:10, five CLSM mixes were prepared for Group-1 study with CKD replacing cement at five levels i.e., 0%, 25%, 50%, 75% and 100%. Water content for each CLSM mix was controlled by achieving a target flowability of around 250 mm by testing flow as per ASTM D6103 (2004).

Various tests for ascertaining the characteristics of each CLSM mix in the fresh and the hardened state were conducted as per relevant standards. The fresh state properties, flowability, unit weight, bleeding, setting time (penetration resistance) and ball drop resistance test were tested. The hardened state properties, unit weight, water absorption, unconfined compressive strength (UCCS), California bearing ratio (CBR), drying shrinkage and permeability were examined. Mineral phases examination through XRD along with microstructural analysis with

FE-SEM and EDS examination was done. Leachate toxicity of the CLSM mixes in terms of heavy metal concentration with TCLP was also tested.

Ecological analysis in terms of embodied energy and embodied carbon of the CLSM mixes of all the groups was also done which is presented in section 4.6.

4.2.1 Flowability

Flowability was tested as per ASTM D6103 (2004) and results for the five CLSM mixes are presented in Table 4.1 and Figure 4.1. The flowability of all the mixes (235-248 mm) attained at around 250 mm was considered a good flowability (above 200 mm) as per ACI 229R (1999). The flowability of the mixes showed that the required flowability was achieved at lower water content for the mixes having higher CKD. Also, maximum flowability was achieved with minimum w/b for the 100 % CKD mix S-CKD-100.

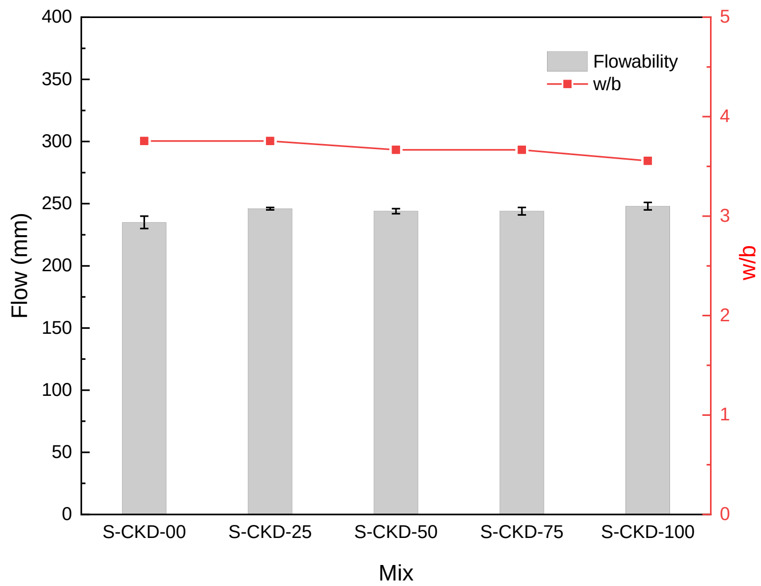


Figure 4.1 Flowability of mixes in Group-1 CLSM

Several factors such as fine contents, gradation of the constituents, their proportions, particle texture/shape and quantity of water, are supposed to affect flowability (Crouch et al., 2004; Deng and Tikalsky, 2008; Dingrando et al., 2004). Increasing finer CKD by replacing the OPC seems to have increased the average grain fineness of the matrix leading to higher flowability. Tikalsky et al. (2004) while studying excavatable and structural CLSM using industrial wastes namely excess foundry sand and fly ash has reported that finer the average grain size of the matrix, lesser the water content required for a specified flow. Also, addition of

CKD might have led to release of water entrapped between cement particles due to increased packing by fine CKD particles filling the voids and resulted an increased flowability (Camiletti et al., 2013; Mneina et al., 2018). Additionally, the lubrication effect of CKD particles by reducing the interference between coarser particles of the matrix might also have increased the flowability. The release of water due to addition of CKD as mentioned above has possibly been more pronounced than the possible rise of water demand due to increased surface area of the finer CKD. The lower w/b ratio with increase in CKD content also indicates lesser consumption of water for preparation of CKD based mixes which is a step towards sustainability. Water is also a costly commodity these days and its lesser consumption ultimately saves costs.

Table 4.1 Fresh state properties of Group-1 CLSM mixes

Mix designation	Fresh Unit weight kg/m^3	Flow (mm)	w/b	Bleeding %	Initial Setting time at PR 0.344 MPa (hrs)	Final Setting time at PR 2.76 MPa (hrs)	Ball drop setting time at Indentation dia-76 mm (hrs)
S-CKD-00	1852	235	3.76	4.85	10.6	38.3	113.5
S-CKD-25	1845	246	3.76	6.00	11.4	39.5	245.4
S-CKD-50	1852	244	3.67	5.83	13.0	68.6	276.0
S-CKD-75	1834	244	3.67	5.64	15.3	120.5	623.4
S-CKD-100	1851	248	3.56	7.88	82.1	873.3	847.8

4.2.2 Fresh state Unit Weight

Unit weight in the fresh state of all the mixes presented in Table 4.1 was found to be between 1834-1852 kg/m^3. The fresh unit weight of the CLSM mixes is very close to the range specified by ACI 229R (1999) for normal CLSM mixes i.e., 1840-2320 kg/m^3. The results at Figure 4.2 show a trend of decreasing unit weight of the CLSM mixes for an increased CKD content. This is attributable to lesser specific gravity (2.57) of CKD which replaced the OPC having a comparatively higher specific gravity (3.10). Similar results on replacement of OPC or other constituents with a lesser specific gravity material have been reported in earlier research studies (Ahadzadeh Ghanad and Soliman, 2021; Lachemi et al., 2008; Mneina et al., 2018; Taha et al., 2007). Fresh unit weight of the proposed mixes is near lower limit of the range for a normal CLSM (ACI 229R, 1999). A lesser unit weight CLSM will cause less overburden upon the underground utility structures which will require relatively cost-effective leaner utility elements like pipes for sanitary/sewerage/telephone or any other service. Lesser consumption of materials for manufacturing/constructing the leaner utility elements further lead to sustainability. Therefore, addition of CKD in replacement of cement in the CLSM is advantageous and S-CKD-75 shall be best with least unit weight.

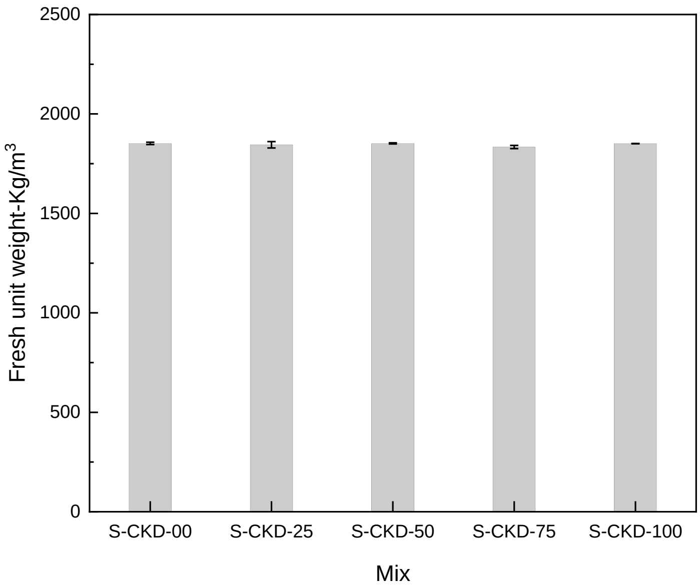


Figure 4.2 Fresh state Unit weight of Group-1 CLSM mixes

4.2.3 Bleeding

Bleeding values observed for the five CLSM mixes presented in Table 4.1 and Figure 4.3 are found to be in the range of 4.85 % to 7.88 %. CKD addition as replacement of cement has resulted in higher bleeding. The trend is not consistent possibly for variation in w/b ratio for the mixes. However, the bleeding was higher for all the mixes with CKD addition compared to mix with 0% CKD. Maximum bleeding was observed for 100% CKD mix even with lowest w/b. Higher bleeding in CKD mixes can be attributed to better packing of constituents resulting from addition of finer CKD as replacement of OPC, which results in release of water entrapped between coarser particles to enhance flow (Mneina et al., 2018). As such the reduced water demand of the mix for the target flowability might have led to higher bleeding. Higher bleeding for increased CKD can also possibly be due to an almost inert nature of the used CKD with very less/no affinity to water as compared to OPC resulting in a lesser water demand for a desired flowability. With addition of CKD as replacement of OPC, the CLSM mix would have lesser degree of hydration and consequently unreacted water increases which causes an increased bleeding similarly as reported in previously (Lee et al., 2013). On the other hand, fineness of added CKD had the potential to increase the water demand owing to the increased surface area and an increased water retention due to refinement of pore structure. However, the reduced water demand due to addition of CKD as mentioned above has possibly overshadowed the impact of fineness of CKD raising the water demand (Camiletti et al., 2013) resulting into a net higher bleeding.

The bleeding values for CKD mixes are above the desirable 5% value suitable for practical applications (Gabr and Bowders, 2000; Park et al., 2017; Zhang et al., 2018). The fine aggregate SFS, which is finer than any conventional fine aggregate, require and retain more water, may have resulted higher bleeding, similar to the bleeding at around 9% reported previously (Deng and Tikalsky, 2008; Tikalsky et al., 2004). Also, it is notable that the higher bleeding up to 8.73% and 7.2% reported by Tikalsky et al. (2004) and Razak et al. (2009) respectively is related to excavatable CLSM. This is attributable to requirement of more water and less cement in order to control the strength development suited for excavatability. Thus, higher bleeding has been considered normal for excavatable CLSM. Addition of CKD resulting in an increased bleeding suggested using a lesser water content to control bleeding and this helps sustainability. Also, reducing the target flowability from 250 mm to a lower value might potentially reduce the bleeding to acceptable levels.

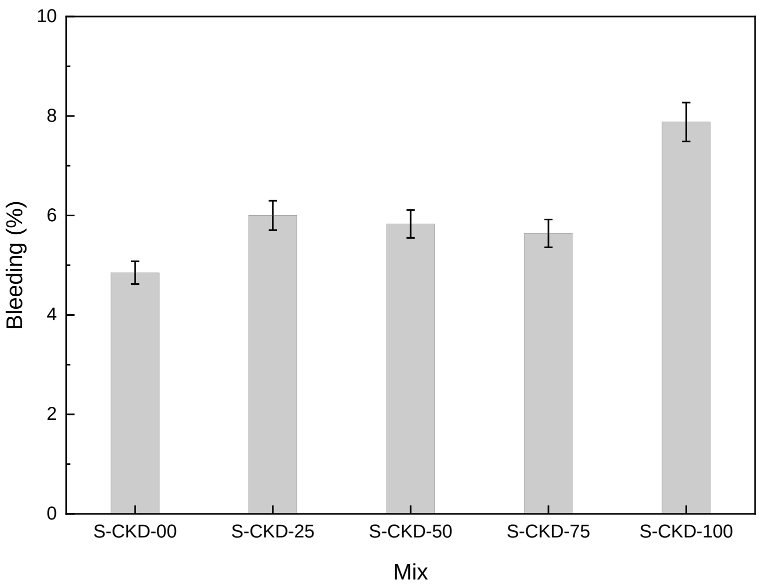


Figure 4.3 Bleeding of Group-1 CLSM mixes

4.2.4 Setting Time

Setting time of the CLSM mixes was examined in terms of both the penetration resistance (PR) and the ball drop resistance. Setting time to arrive at penetration resistance of

0.344 MPa and 2.76 MPa have been examined. Penetration resistance of 0.344 MPa and 2.76 MPa are significant stages in the strength gain process of CLSM in respect of the allowing the intended load application.

PR versus setting time plots for different CLSM mixes are shown in Figure 4.4. Results of initial and final setting time are reported in Table 4.1. Initial setting times for the CLSM mixes with up to 100 % CKD content as replacement of cement ranged between 10.6-82.1 hours and final setting time between 38.3-873.3 hours. The PR versus time plots for the CLSM mixes showed that the setting time increased with an increasing cement replacement by CKD. Higher setting time can be owed to the use of CKD for its very low/insignificant strength contribution to CLSM. Previous researchers have even considered CKD as inert (Lachemi et al., 2008; Marku et al., 2012). Further, the addition of CKD as replacement of OPC in the mixes also rendered lesser strength giving reactants like C_2S and C_3S etc. in the mixes resulting into less strength gain. Di-calcium silicate C_2S and tri-calcium silicate C_3S are major components of cement contributing majorly towards strength through hydration. Similar enhancement of initial and final setting time due to increased CKD (from 4 sources) content from 4 to 30 % in the CLSMs attributed to decreased cement content has been reported (Lachemi et al., 2008). High bleeding 4.85 % to 7.88 % witnessed in the CLSM also reflected the increased setting time, hardening time, reduced strength (Zhang et al., 2018). Further, it was quite important to see that the required PR was achieved by the CLSM mix even with 100% cement replacement. Which meant that even by use of only the industrial by-products as the constituents, the desirable setting level was achievable although after some longer setting time. With respect to application, the mixes were suitable for several situations wherein allowing human and vehicular traffic is unlikely before the respective setting time. It is also pertinent to bring out that addition of even small content of OPC resulted a reasonable setting time level for the CLSM mixes. This is in view of the fact that with only 25% OPC addition, initial and final setting time have decreased from 82.1 and 873.3 to 15.3 and 120.5 hours. The mix S-CKD-75 using quite higher replacement level of 75 % CKD shall be best with respect to setting time (PR).

Setting times as per ball drop resistance for 76 mm indentation diameter are in the range of 113.5-847.8 hours as mentioned in Table 4.1. Indentation diameter versus elapsed time graphs provided in Figure 4.5 show the setting time for achieving 76 mm indentation for all the mixes. The results depict an increase in ball drop setting time with increasing replacement of OPC with CKD. The ball drop setting time was up to 276 hours for the mixes till the 50 %

CKD replacement level. Beyond 50 % CKD replacement, the time required to achieve 76 mm indentation increased significantly.

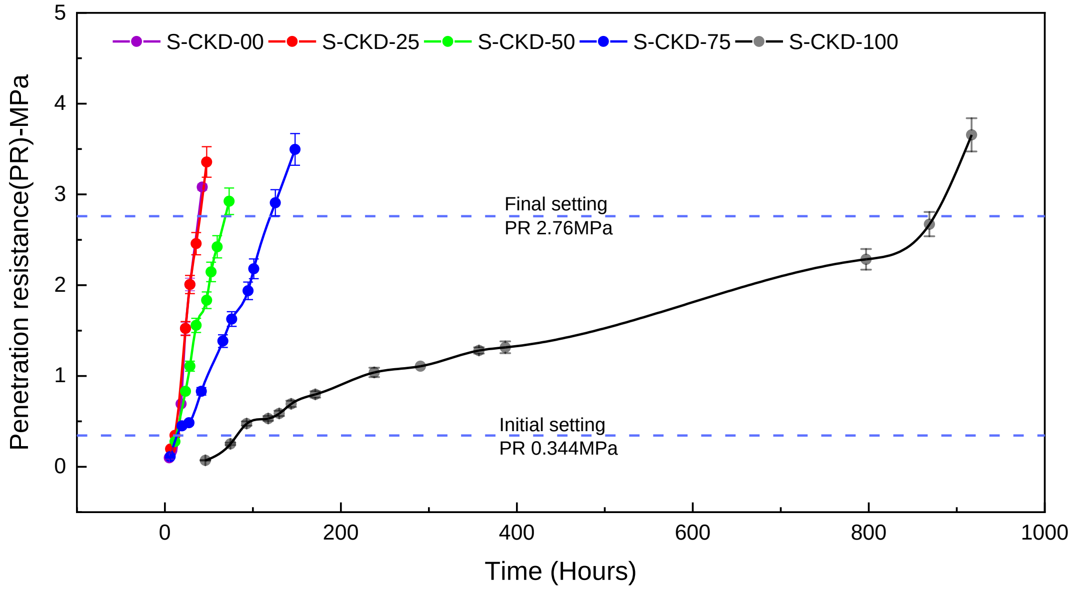


Figure 4.4 Setting time as per Penetration resistance Vs Time of Group-1 CLSM mixes

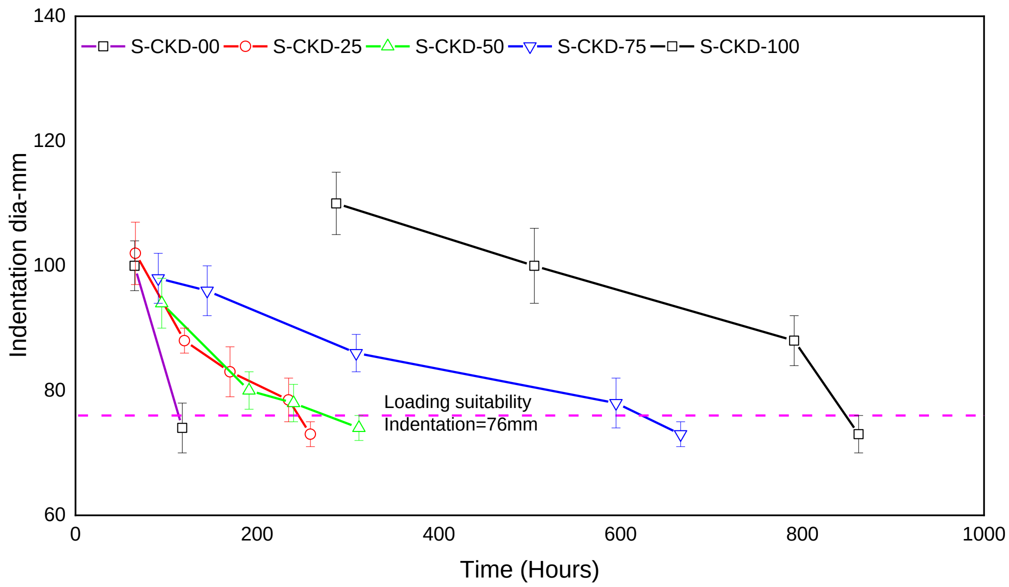


Figure 4.5 Setting time as per Ball drop indentation Vs Time of Group-1 CLSM mixes

The mixes with longer setting time may be considered as non-structural/excavatable CLSM where setting time and early strength are not critical like general backfill applications like void-filling, filling abandoned underground-structures etc. (Ling et al., 2018a). Abandoned mine cavities also require filling for ensuring safety of the area above the mine (Carsana and Bertolini, 2012).

4.2.5 Hardened state Unit weight and water absorption

Unit weight and water absorption for hardened CLSM are significant properties for evaluation of loading or lateral thrust in construction activities because these change with time after placement (Wu and Lee, 2011). The unit weight of all the samples in both as unmoulded (AU) condition and in oven dried (OD) condition was measured at 28 days. The OD unit weight was also used to ascertain water absorption of the mixes. The results are presented in Table 4.2 and Figure 4.6. AU unit weight of the mixes ranged between 1547-1855 kg/m^3 and OD unit weight between 1403-1585 kg/m^3. The hardened unit weight are lesser than the unit weight of 1650 kg/m^3 for a compacted earth fill (Wu and Tsai, 2008). As expected, OD unit weight is substantially lower than the AU unit weight of the CLSM due to loss of moisture (ACI 229R, 1999). Results show an increase in both AU and OD unit weights with increasing CKD proportion in binder. This could be due to higher CKD levels causing increased bleeding and more settlement of CLSM grout i.e., more compact mix resulting to a higher hardened density. Addition of finer CKD particles as replacement of cement possibly led to better packing of the constituents in the mix leading to higher density.

Water absorption potential values for the four CLSM mixes are between 26.25 to 27.43 %. Water absorption of the mix with 100 % CKD could not be ascertained as the specimen crumbled during immersion in water owing to inadequate binding. Addition of CKD as replacement of cement did not seem to impact the absorption significantly. Water absorption of hardened CLSM would be related to its porosity. Porosity is related to water demand for desired flowability which is also further dependent upon constituent proportions and their characteristics like surface texture, solid or porous structure. SFS particles used as aggregate in this group had a very low water absorption and therefore might not have affected porosity of the hardened mix. However, high water content is generally needed for achieving desired flowability which is a key requirement of a CLSM leading to higher water to solids ratio in the mix. Wu and Lee (2011) have observed that for the sample with a higher water to solids ratio, its hardened state would result in higher volume of permeable pore space leading to a higher water absorption. Water absorption at the level of around 12-35 % for CLSM mixes has also been reported earlier by Razak et al. (2010).

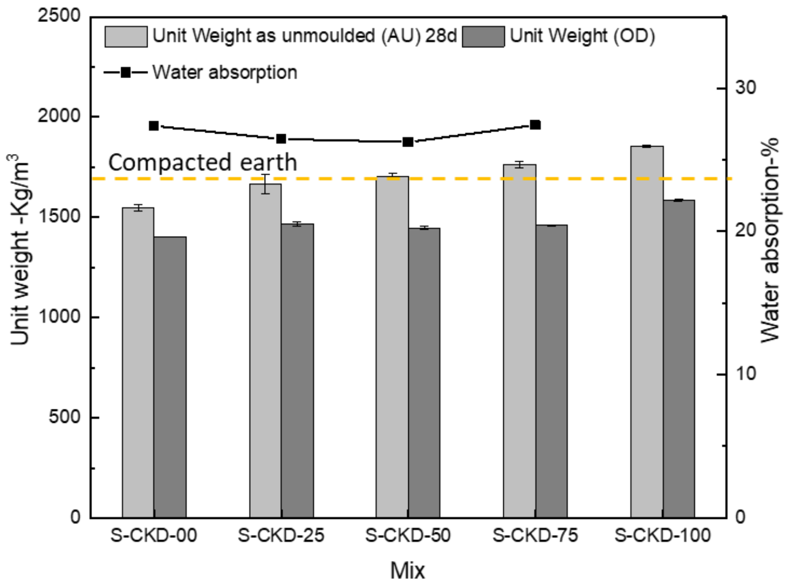


Figure 4.6 Hardened state Unit weight of Group-1 CLSM mixes

Table 4.2 Hardened state properties of Group-1 CLSM mixes

Mix	Unit wt. (As unmoulded (AU) 28 days) (kg/m^3)	Unit wt. (OD) (kg/m^3) (% of unmoulded weight)	Water absorption (%)	Unconfined compressive strength (UCCS) (MPa)			CBR at ball drop setting time %	Drying shrinkage (%) (days in air)			Coefficient of Permeability 'K' cm/sec
				28 days	56 days	91 days		25	53	81	
S-CKD-00	1546.7	1403.3 (90.7%)	27.38	0.594	0.736	0.946	34.9	0.1116	0.1523	0.1602	10.30x10-4
S-CKD-25	1665.7	1467.3 (88.0%)	26.46	0.411	0.512	0.681	33.1	0.1405	0.1592	0.1621	2.46x10-4
S-CKD-50	1703.0	1448.8 (85.0%)	26.25	0.359	0.369	0.397	26.9	0.1330	0.1506	0.1565	4.07x10-4
S-CKD-75	1762.8	1459.2 (82.8%)	27.43	0.146	0.162	0.179	19.6	0.1607	0.1998	0.2335	2.39x10-4
S-CKD-100	1855.5	1584.7 (85.4%)	X	0.063	0.076	0.091	10.9	X	X	X	X

'XX' indicate that the test could not be performed since the specimen crumbled

4.2.6 Unconfined Compressive Strength

Unconfined compressive strength (UCCS) of the prepared CLSM mixes is presented in Table 4.2 and shown in Figure 4.7. The UCCS values are in the range of 0.063-0.594 MPa, 0.076-0.736 MPa and 0.091-0.946 MPa at 28 days, 56 days and 91 days respectively. It was observed that the UCCS reduced with increasing levels of CKD in binder. It could be attributed to an almost inert nature of CKD, with very low contribution towards strength as compared to OPC (Al-Harthy et al., 2003; Lachemi et al., 2010; Udoeyo and Rindap, 2002). Addition of CKD in place of cement reduces calcium silicates (C_3S, C_2S) which are major reactants in cement contributing towards hydration and strength (Najim et al., 2014). Also, the CKD having high percentage of LOI (22 %) and SO_3 (6 %) potentially reduced the compressive strength (Adaska and Taubert, 2008; Pierce and Williams, 2012). High LOI dusts have higher percentage of bound water within its chemical structure and less CaO available to react and high SO_3 retards setting. Paste volume ratio (PVR) i.e., ratio of paste (Cement, water and SCM) to total volume increases with increasing CKD replacement due to its lower specific gravity than cement. Increasing PVR might have caused decrease in strength related to crack tortuosity as a crack needs a shorter path to traverse from one side to other side of the sample with high paste content (Alizadeh, 2019; Kolias and Georgiou, 2005).

Also, the strength gain rate over the curing age reduced with the increase in replacement of cement with CKD. This indicates insignificant contribution of CKD towards long-term strength. In CLSM mixes, long term strength needs active consideration since CLSM with an accepted early age strength (i.e., at 28 days) may still continue gaining strength and make the future excavation difficult (Lachemi et al., 2008). Monitoring long term strength becomes more relevant in view of recent reportage of strength gain beyond 28 days in CLSM research (Kim et al., 2018; Wu et al., 2016). Excavatability is governed by long-term strength of CLSM and all the mixes in Group-1 study qualified as excavatable CLSM with their maximum 91 days UCCS (0.95 MPa for 0 % CKD mix) being less than 2.1 MPa (ACI 229R, 1999). Further, all mixes using CKD i.e., CKD 25 % and above, have 91 days UCCS below 0.70 MPa which indicated the mixes using CKD to be excavatable either manually or with conventional digging equipment. However the mix with 0 % CKD i.e., with only OPC, having the 91 days UCCS above 0.70 MPa, was excavatable only mechanically (ACI 229R, 1999).

In terms of application, the mixes with 28 days UCCS less than 0.50 MPa (S-CKD-25, S-CKD-50, S-CKD-75 and S-CKD-100) could be suitable for general backfilling applications like void filling, abandoned underground structures (Ling et al., 2018a). Mix S-CDKD-00 with 28 days UCCS between 0.50-2.10 MPa and early setting shall be suitable for excavatable utility backfilling such as underground pipe lines (for water, sewer), roadway trench and conduit bedding etc.

Development of excavatable CLSM utilizing minimum or no-cement but high content of industrial waste by-products namely CKD and SFS was feasible along with providing added advantage of sustainability. Excavatability, manually or with conventional equipment, of all the mixes using CKD also contributed to sustainability in terms of saving of energy in comparison with requirement of a mechanical equipment needed for excavating a CLSM of higher unconfined compressive strength. Mix S-CKD-75 using maximum by-products would prove best with respect to the aspect of its application, excavatability as well as sustainability.

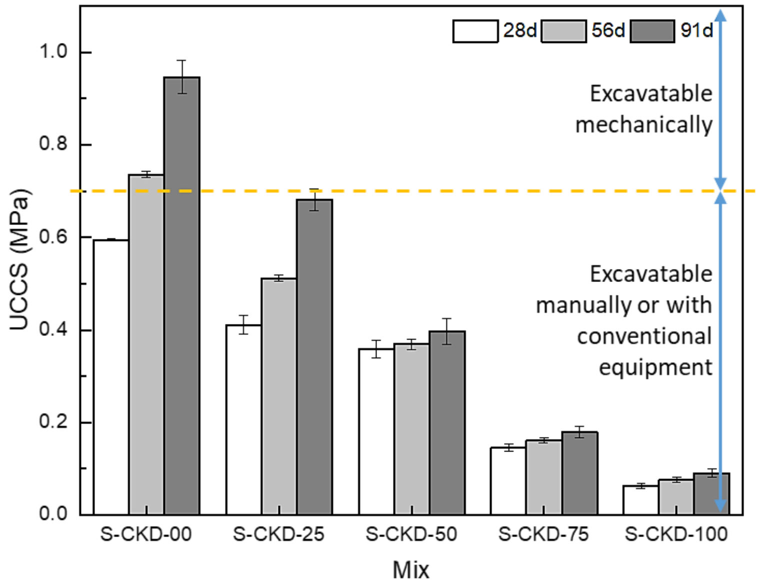


Figure 4.7 Unconfined compressive strength (UCCS) of Group-1 CLSM mixes

4.2.7 California Bearing Ratio (CBR)

CBR values for the CLSM mixes were measured at the age of ball drop setting time (76 mm indentation). The CBR values obtained as reported in Table 4.2 and shown in Figure 4.8 are found to be in the range of 10.9-34.9%. It is seen that the CBR of the CLSM decreased with the addition of CKD as replacement of OPC. Progressive CKD addition by reduction of cement in the mix caused a reduction of strength and being a strength related parameter, CBR also reduced accordingly. CBR value of the CLSM mixes also reflect the bearing strength of the backfilled layer with that CLSM (Thaha, 2007). Further, a subgrade layer of sand can be categorized as well compacted sand if its CBR value is in the range of 10-25 % and very well compacted sand when CBR is between 25-50 % (Knapton, 1999). Based on above categorization, the developed mixes S-CKD-00 to S-CKD-50 can support pressure equivalent to a 'very well compacted sand' and S-CKD-75 and S-CKD-100 equivalent to a 'well compacted sand'. Also, the test results of CBR and UCCS indicate that CBR is positively correlated with UCCS. Similar observations have also been made by previous researchers (Lachemi et al., 2008; Naganathan et al., 2012). Results also indicate that the ball drop setting time and CBR are negatively correlated. All the CLSM mixes using CKD and categorized on basis of CBR as equivalent to a well/very well compacted sand can serve as a strong fill.

Additionally, S-CKD-75 presents the maximum suitability in terms of having a reasonable CBR along with other important aspects like setting time and sustainability.

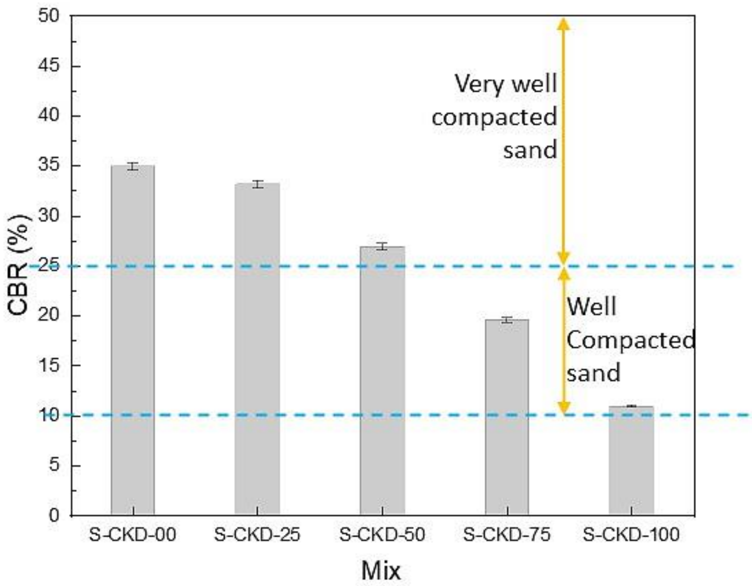


Figure 4.8 California bearing ratio (CBR) of Group-1 CLSM mixes

4.2.8 Drying shrinkage

Percentage shrinkage values are presented in Table 4.2 and the shrinkage vs time graphs are presented at Figure 4.9. It is to mention here that the shrinkage testing of only four mixes could be performed since the specimens with 100 % CKD could not withstand the demoulding process due to no/very low strength achieved and they broke. Study of the drying shrinkage results depict that drying shrinkage increased with time of drying. Further, the shrinkage increased at a faster rate for the initial duration of about 25 days and slowed thereafter and appears to have almost reached the ultimate level at 81 days.

When comparing the results, it is observed that the initial values of drying shrinkage increased with increasing CKD level in the CLSM mix. However, the final shrinkage of all the mixes were comparable, with the exception of S-CKD-75 which had higher drying shrinkage throughout the testing duration. The trend of higher shrinkage with higher CKD content may be attributed to the phenomenon of water retention by finer CKD particles which cause drying from the bulk rather than from the surface (Katz and Kovler, 2004). Also, initial increase in drying shrinkage due to addition of CKD as replacement of cement led to two concurrent effects in the mix; namely dilution and filling. Diluting means there is less OPC in the system which will make lesser hydration products and consequently result in slow disruption of capillary pores. Also, the lesser hydration products with proportionally lesser consumption of water will make availability of more free water for evaporation leading to more shrinkage. Filling means, addition of finer material that fill large voids of other constituents in the mix and result in a finer pore structure leading to higher internal stresses and hence higher shrinkage (Mneina et al., 2018). Both these factors led to higher shrinkage of CLSM mixes with CKD. Higher shrinkage of pastes made with fine inert material (treated oil sand waste) as cement replacement were similarly observed (Aboutabikh et al., 2016). Addition of CKD leading to increased PVR might have also caused higher shrinkage (Alizadeh, 2019). Mixes with up to 50 % CKD, S-CKD-25 and S-CKD-50 had the same long-term shrinkage as of mix with 100 % OPC i.e., S-CKD-00 while the mix S-CKD-75 had somewhat higher shrinkage. However, it does not affect CLSM's performance (ACI 229R, 1999).

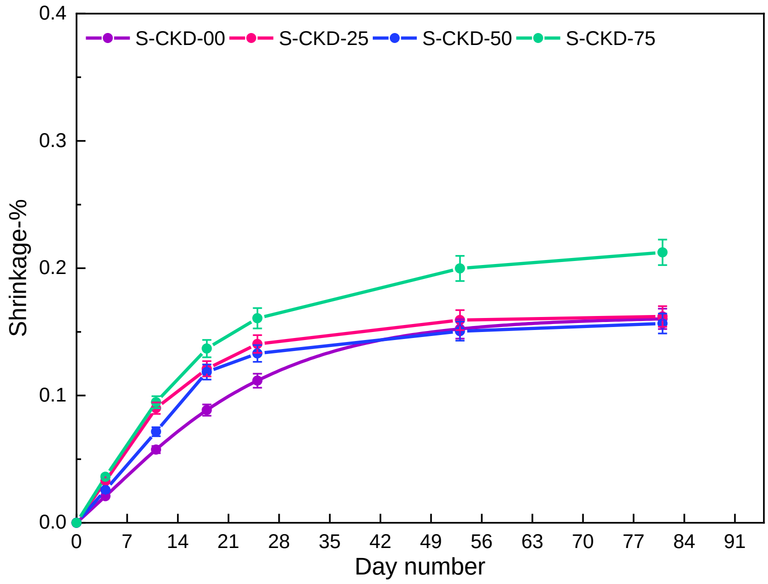


Figure 4.9 Drying shrinkage versus Time of Group-1 CLSM mixes

4.2.9 Permeability

Coefficient of permeability (K) for the CLSM mixes as presented in Table 4.2 and Figure 4.10 is found to be in the range of 10.3×10^{-4} to 2.39×10^{-4} cm/sec. The results indicate a drastic reduction of permeability with addition of 25 % CKD as replacement of OPC but no significant change is observed for more than 25 % CKD level. A similar variation in permeability showing significant reduction in permeability for addition of 15 % cement by pass dust along with a quite less effect for above 15 % level has been reported in literature (Ata et al., 2015). The reduction in permeability is possibly attributable to the filling/packing effect by fine inert CKD particles into the voids of coarser SFS particles leading to refinement of pore structure of the matrix. Permeability of granular soils is also reported to be related to average grain size (Terzaghi et al., 1996) and reduction of the grain size due to addition of finer CKD in the mix seems to have resulted in to a decreased permeability. Al-Harthy et al. (2003) have also reported a decreased hydraulic conductivity in terms of sorptivity due to finer CKD replacing cement in the concrete. All CKD mixes (25-75% level) have lower permeability than the mix with 0% CKD permeability also reduced with higher CKD level. The anomalous lower permeability value of 25% CKD mix compared to higher CKD level mixes may be taken up in the scope of future studies. Hydraulic conductivity or permeability is an important parameter from the environment point of view as lower permeability is helpful in reducing leaching (Tikalsky et al., 2004).

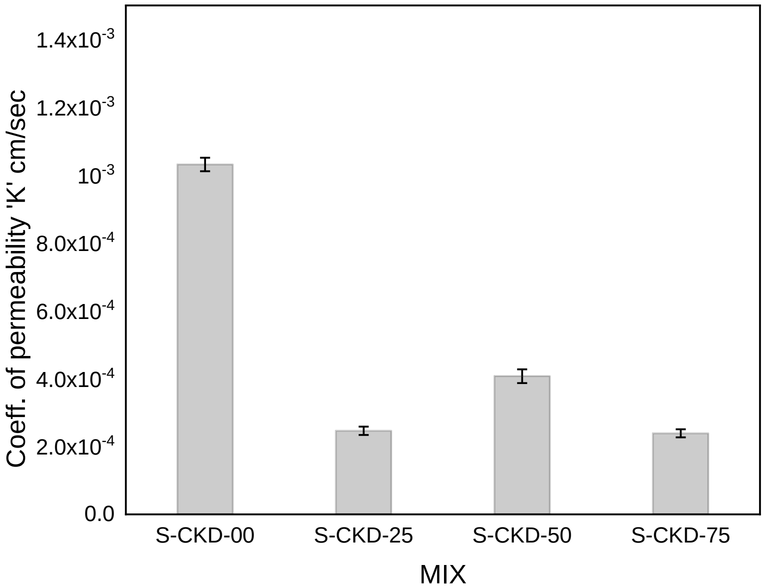


Figure 4.10 Coefficient of Permeability 'K' of Group-1 CLSM mixes

The coefficient of permeability of CLSM in this study is around the range of 10^{-4}-10^{-5} cm/sec attributed to most excavatable CLSM, compacted granular fills (ACI 229R, 1999) and clean sands having good drainage (Terzaghi et al., 1996). As the permeability is considered as a desirable property for general backfill, utility trench backfill purposes and insulating and isolation fill (Wu et al., 2016), the CLSM mixes under study shall be suitable for these applications. All proposed mixes have permeability in the desirable range but the mixes using CKD shall be additionally beneficial in terms of sustainability also.

4.2.10 Mineral phase identification (XRD) and microstructure (FESEM, EDS)

The XRD scanning upon powdered CLSM specimen (post 28 days unconfined compressive strength testing) was done and the mineral phase identification is shown in Figure 4.11.

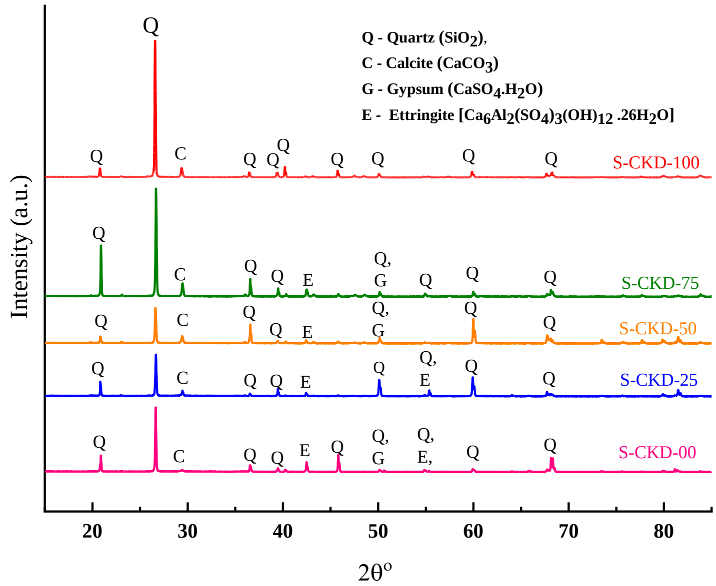
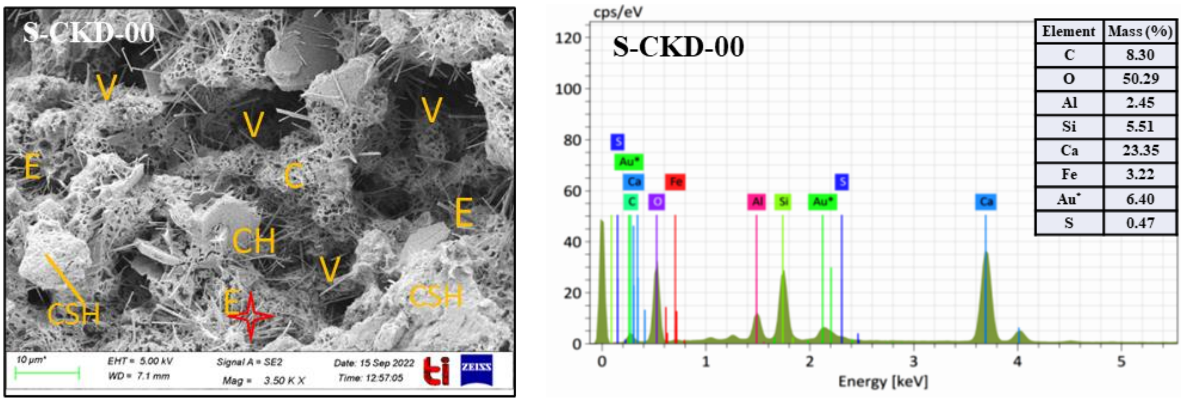


Figure 4.11 XRD scan of Group-1 CLSM mixes

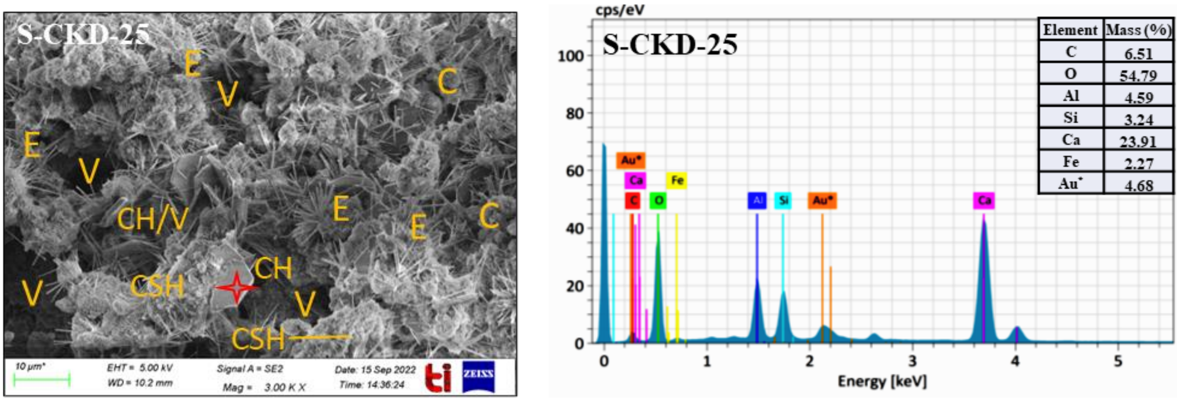
Main phases identified are, quartz (Q), gypsum (G), calcite (C), and ettringite (E). The hydration product ettringite phases are observed in all mixes except S-CKD-100. Presence of hydration products indicate the occurrence of strength activity in the mixes having some cement content in the binder combination. Absence of hydration products in S-CKD-100 indicates the use of an almost inert CKD. Accordingly, it was observed that the mixes having some cement content achieved higher UCCS in comparison to the minimum strength for the mix with no cement (S-CKD-100). Similar observations regarding hydration products and mechanical strength related to cement content have been reported in previous research (H. Liu et al., 2022). Presence of gypsum phases in hardened CLSM seen, represent a low reaction owing to insufficient hydration reactants. Except for proportions, no qualitative change in phase composition is observed across different CLSM mixes with varying CKD/Cement percentage as binder, which also indicate an almost inert nature of CKD. Similarly, Vardhan et al. (2015) observed no qualitative change in phase composition with incorporation of an inert material, marble powder as replacement of cement in the mortar.

Broken pieces of the CLSM mix specimens (after UCCS testing) were gold (Au) coated and examined using field emission scanning electron microscopy (FE-SEM) for microscopic imaging and energy dispersive X-ray spectroscopy (EDS) techniques for identification of elemental composition. The FE-SEM images and EDS scans of different CLSM mixes are presented in Figure 4.12 (a)-(e).

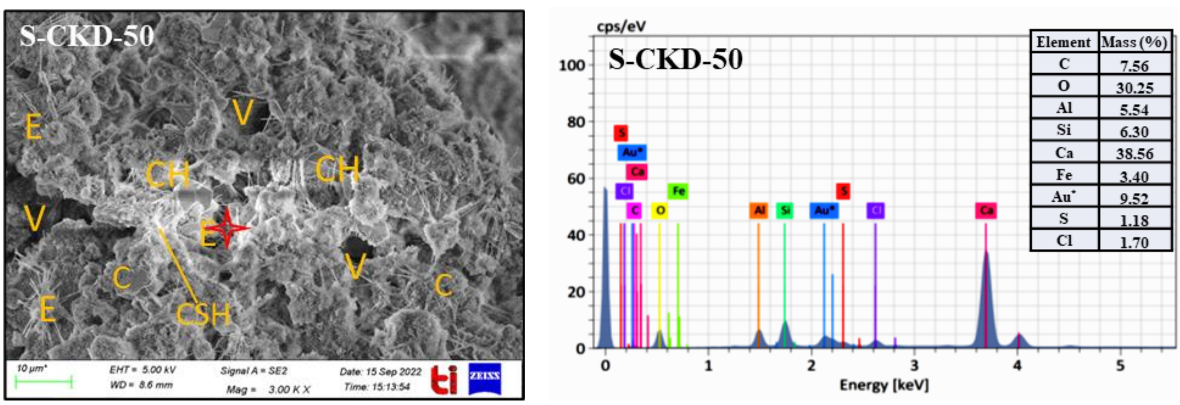
The CLSM mixes have a very low cement component that is further being reduced by the CKD and SFS is a low-grade fine aggregate. Therefore, the small and diminishing presence of common hydration products namely calcium hydroxide/portlandite (CH), calcium silicate hydrate (CSH), calcite ($CaCO_3$), ettringite (E) as seen in the FE-SEM images for the mixes with higher CKD is as expected.



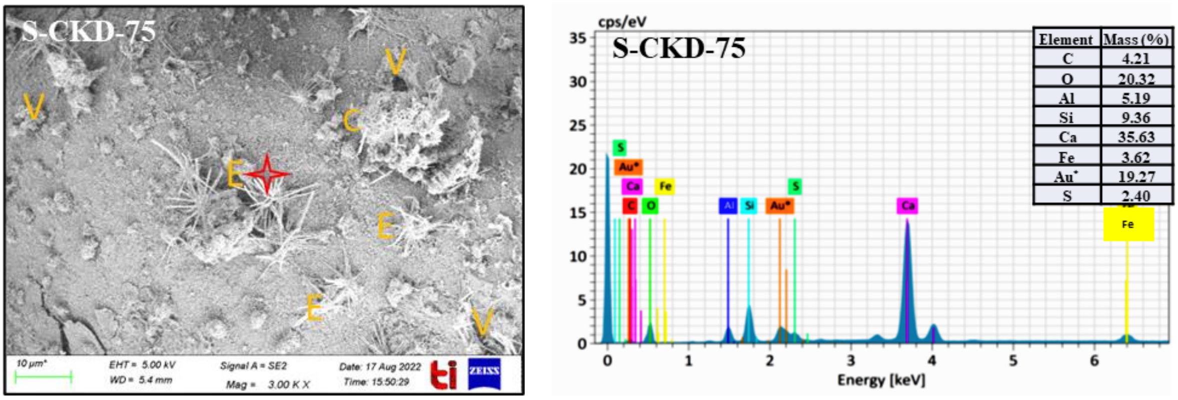
(a)



(b)



(c)



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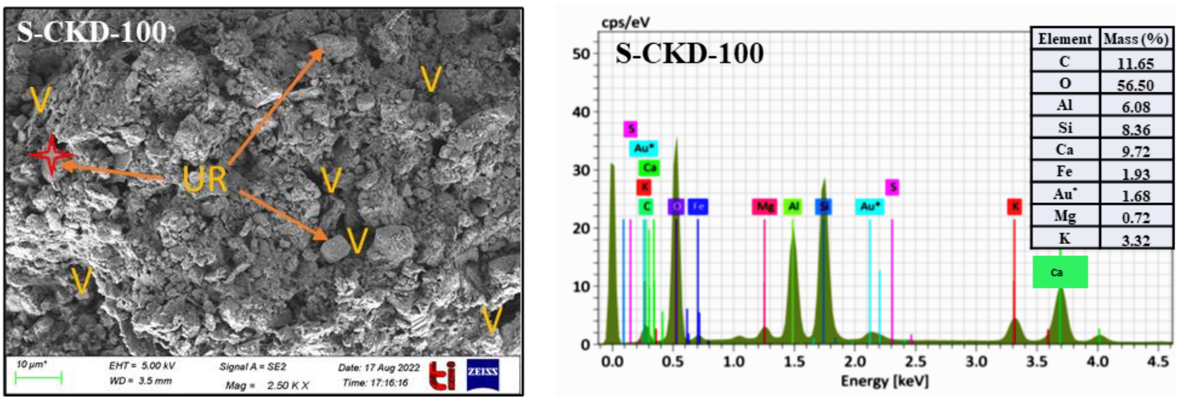


(e)

Figure 4.12 FE-SEM and EDS image of Group-1 CLSM mixes (a) S-CKD-00; (b) S-CKD-25 (c) S-CKD-50 (d) S-CKD-75 and (e) S-CKD-100

Phases of calcite (C) along with one or more hydration products such as CSH, E, and CH are observed in the images of mixes having CKD up to 75% in binder i.e. up to 25% cement in binder. No hydration products, but only unreacted particles (UR) of constituents SFS and CKD were observed in the mix having 100% CKD as binder, which also indicated the inert nature of CKD. Absence of hydration products/strength activity in S-CKD-100 is reflected by no binding between constituent particles, since the specimens crumbled in water during immersion for conducting hardened unit weight/absorption and permeability test. Whatever binding/strength is observed in S-CKD-100, might be the result of interlocking between particles of constituents aided by the effect of bentonite in the spent foundry sand. Evidence of ettringite at 28 days is indicative of further hydration and strength gain at later age (Do et al., 2019). This is validated by the higher unconfined compressive strength of the CLSM at 56 days and 91 days as compared to 28 days. Lesser voids (V) with increasing CKD reflected decreasing porosity/permeability in line with the permeability results.

Chemical composition of all the mixes by EDS analysis are tabulated in Table 4.3. Major reactants in the mixes are Si, Al and Ca. Ca value is highest in S-CKD-00 with 100 % cement and lowest in mix S-CKD-100 with 100% CKD is possibly reflecting the calcium comparison in binder source. Si/Al ratios 3.39, 2.86, 3.79, 2.44 for mixes S-CKD-00 to S-CKD-75 respectively and a relatively higher value of 4.91 for S-CKD-100 indicate a general rising trend among majority of Si/Al ratio of mixes with the addition of CKD. Reducing UCCS of the CLSM mixes with increasing CKD content is reflected by higher Si/Al ratio similarly as reported in literature (Chindaprasirt et al., 2009; Ho et al., 2022; Hwang et al., 2017).

Table 4.3 EDS analysis of Group-1 CLSM mixes

CLSM	Values by mass (%)			Si/Al
	Si	Al	Ca	
S-CKD-00	9.74	2.87	27.84	3.39
S-CKD-25	8.79	3.07	22.44	2.86
S-CKD-50	11.61	3.06	23.61	3.79
S-CKD-75	6.74	2.76	23.92	2.44
S-CKD-100	11.50	2.34	17.76	4.91

4.2.11 Leachate Toxicity

Environmental impact in respect of toxicity of leachate was examined by conducting Toxicity Characteristics Leachate Procedure (TCLP) upon the broken pieces of CLSM specimen remaining after unconfined compressive strength test. The reagent grade water, as specified in TCLP as per USEPA Method 1311 (USEPA-1311, 1992), was used for the preparation of extract liquid for leachate study. Concentrations levels of toxic metals such as Lead (Pb), Cadmium (Cd), Copper (Cu), Chromium (Cr), Zinc (Zn), Nickel (Ni), Barium (Ba), Lithium (Li), Strontium (Sr) and Magnesium (Mg) were worked out through Microwave Plasma Atomic Emission Spectrometer (MP-AES) analysis and are presented along with regulatory limits or parametric values in Table 4.4.

Parametric values for some elements are as per limits for hazardous waste as per US Code of Federal Regulations titled 'Identification and Listing of Hazardous Waste' (CFR-2021-title40-vol28-part261, 2021). For other elements which are not in the above list, a value equivalent to 100 times the levels of US ‘Drinking Water Standards and Health Advisories’ (USEPA, 2018) or the Indian Standard Drinking Water Specifications (Bureau of Indian Standards, 2012) have been considered. 100 times the concentration limits of toxic metal for drinking water have been considered as the Toxicity Standard presuming that 100 times dilution would occur before the leachate could reach drinking water (Patel and Pandey, 2012; Tikalsky et al., 1998; Wartman et al., 2004). All the CLSM mixes in the Group-1 study showed heavy metal concentrations below the regulatory/parametric limits. Therefore, use of by-products CKD and SFS in the developed CLSM shall be non-hazardous and safe and CLSM safe for consideration as a backfill material.

Table 4.4 Toxic metal concentration as per TCLP of Group-1 CLSM mixes

Heavy Metal	Metal concentration (mg/L) in CLSM					Parametric value (mg/L)
	S-CKD-00	S-CKD-25	S-CKD-50	S-CKD-75	S-CKD-100	
Pb	0.31	0.34	0.35	0.38	0.37	5
Cd	<0.01[a]	<0.01[a]	<0.01[a]	<0.01[a]	<0.01[a]	1
Cu	<0.05[a]	<0.05[a]	<0.05[a]	<0.05[a]	<0.05[a]	130[b]
Cr	<0.05[a]	<0.05[a]	<0.05[a]	<0.05[a]	<0.05[a]	5
Zn	0.05	0.87	0.57	0.93	1.00	500[b]
Ni	<0.05[a]	0.05	0.05	0.05	0.05	70[b]
Ba	1.16	1.87	1.10	1.05	0.48	100
Li	0.05	<0.05[a]	<0.05[a]	<0.05[a]	<0.05[a]	-
Sr	2.96	3.28	3.41	3.82	4.41	2000[b]
Mg	28.4	28.9	24.3	18.3	19.9	3000[c]

1.'a'-Below Detection Limit
2. Parametric values are USEPA TCLP limits for hazardous waste as per USEPA regulations CFR-2021-title40-vol28-part261 'Identification and Listing of Hazardous Waste'
3. 'b'-100 times levels as per USEPA document EPA 822-F-18-001 'Drinking Water Standards and Health Advisories'
4. 'c'- 100 times levels for the Indian Standard Drinking Water Specifications IS:10500.

4.3 PROPERTIES OF THE GROUP-2 CLSM MIXES *(Cement + Cement Kiln Dust binders and unprocessed Rice Husk Ash as fine aggregate)*

Five mix proportions were considered for experimentation with the objective of maximizing utilization of industrial by-products with increased replacement of OPC by CKD, both taken as binders. The binder to aggregate ratio was 1:3 and five CLSM mixes were prepared for Group-2 study with CKD replacing cement at five levels i.e., 0 %, 25 %, 50 %, 75 % and 100 %. Water content the CLSM mixes was evaluated for achieving a target flowability of between 200-250 mm as per ASTM D6103 (2004). The constituents' proportioning for CLSM mixes Group-2 are presented in Table 3.12.

Similar to Group-1, various tests in fresh and the hardened state for CLSM mixes in Group-2 were also conducted. Additionally, mineral phases examination, microstructural analysis and ecological analysis were also done.

4.3.1 Flowability

A constant water/binder ratio of 8.25 was found suitable for achieving the target flowability between 200-250 mm for the CLSM mixes. Flowability results for the CLSM mixes presented in Figure 4.13 and Table 4.5 showed that the addition of CKD as replacement of OPC resulted in an increased flowability. Notably minimum flow 220 mm was observed for the mix with 0 % CKD and maximum flow of 242 mm for the mix with 100 % CKD i.e., no OPC. Similar to the Group-1 CSLM mixes, addition of finer CKD particles leading to reduced average grain size of the matrix resulting into less water demand (Tikalsky et al., 2004) and increased packing and lubricating effect of inert CKD particles (Camiletti et al., 2013; Mneina et al., 2018) increased flowability. Also, the unprocessed RHA used in the study was poorly or uniformly graded with particles ranging between narrow range of sizes (0.075-0.55 mm). Addition of fine CKD particles improved the gradation or resulted in wider particle size distribution of the matrix causing a reduced water demand which would also result in a higher flow (Aiqin et al., 1999; Hawkins et al., 2005). Additionally, increase in flow could be also be due to presence of fine RHA particles in the matrix. Cement particles because of surface electric charge absorb fine RHA particles and disperse after trapping large volume of water in a system (Givi et al., 2010b; Mehta, 2004). Addition of CKD causing reduction of cement in the mix resulted in less absorption of fine RHA particles and the associated lesser water trapping i.e., availability of more water in the mix increased the flow. All above factors causing higher flow had more influence than the normal effect of adding fine particles (higher surface area) raising the water demand. The CKD mixes requiring comparatively lesser water content per unit volume of CLSM make them sustainable.

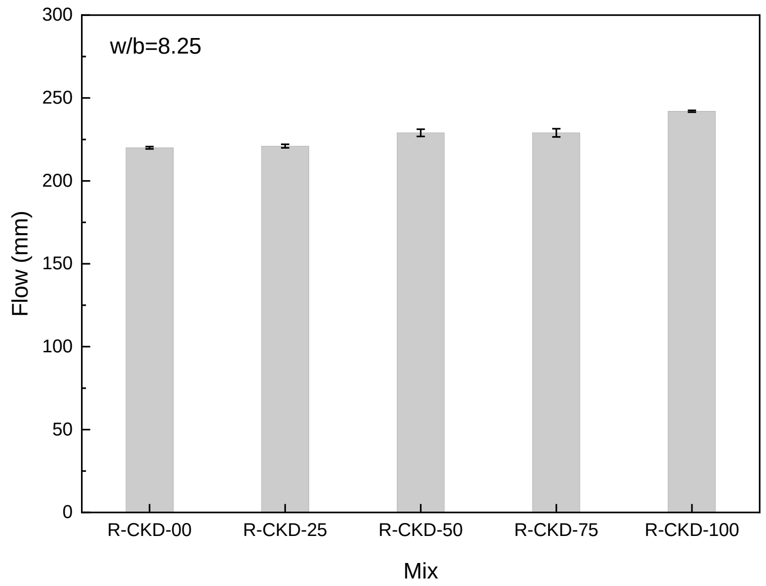


Figure 4.13 Flowability of Group-2 CLSM mixes

4.3.2 Fresh state Unit weight

Fresh unit weight for Group-2 CLSM mixes presented in Table 4.5 and Figure 4.14 ranged between 1225-1242 kg/m^3 with maximum value observed for 0 % CKD mix and minimum for 100 % CKD mix. The fresh unit weights of all mixes are below the wet unit weight range of 1840-2320 kg/m^3 for a normal CLSM but almost near the lower value of the range 1360-1760 kg/m^3 for pond/basin ash CLSM specified in ACI 229R (1999). It is to be noted that lower unit weight are resulted by use of lightweight aggregates, air-entrained constituents or foamed mix (ACI 229R, 1999). Accordingly, use of highly porous RHA with a low specific gravity (1.51) as a major constituent of CLSM caused the lower fresh unit weight compared to a normal CLSM which generally constitute heavier natural sand of specific gravity (around 2.6) as fine aggregate. Attributed similarly to low specific gravity of RHA, use of 100 % RHA as fine aggregate reduced the fresh unit weight of self-compacting concrete by around 30 % (Sua-Iam and Makul, 2013). Further, fresh unit weight of the CLSM mixes decreased with the addition of CKD as cement replacement, which was attributable to lower specific gravity (2.57) of the CKD in comparison to (3.10) of cement similarly as in Group-1. Therefore, use of lighter by-products RHA and CKD as replacement of conventional constituents such as natural fine aggregate, cement has been advantageous in reducing unit weight. Light fresh unit weight CLSM shall exert less lateral pressure therefore shall be suitable as backfill behind formwork in trenches. Lightweight CLSM in a construction application will require leaner embedded elements and resultantly consume less raw materials, and shall be cost-effective and sustainable.

Table 4.5 Fresh state properties of Group-2 CLSM mixes

Mix Designation	Fresh Unit weight kg/m^3	Flow (mm)	w/b	Bleeding (%)	Initial Setting time at PR 0.344 MPa (hrs)	Final Setting time at PR 2.76 MPa (hrs)	Ball drop setting time at Indentation dia-76 mm (hrs)
R-CKD-00	1242	220	8.25	6.22	12.1	215.9	1116
R-CKD-25	1240	221	8.25	5.15	18.9	254.7	X
R-CKD-50	1233	229	8.25	7.77	28.6	597.5	X
R-CKD-75	1230	229	8.25	7.63	46.8	X	X
R-CKD-100	1225	242	8.25	11.08	189.8	X	X

'X'-Mix could not attain desired setting level

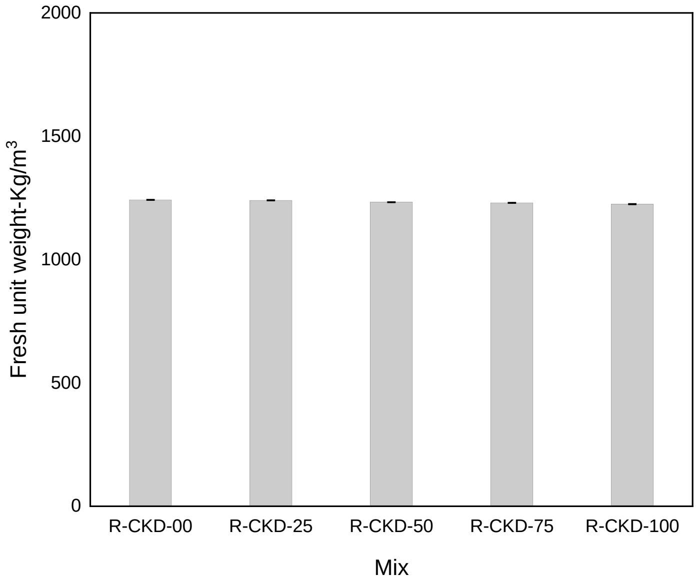


Figure 4.14 Fresh state unit weight of Group-2 CLSM mixes

4.3.3 Bleeding

The bleeding results of the Group-2 CLSM mixes presented in Table 4.5 and shown in Figure 4.15 ranging between 5.15 to 11.08 % depict a trend of enhanced bleeding with the addition of CKD. Finer CKD particles resulting into wider particle size distribution of the constituents with reduced water demand led to higher bleeding (Aiqin et al., 1999; Hawkins et al., 2005). Addition of inert CKD in replacement of cement would be requiring lower water content for hydration and making available more free water in the mix to increase bleeding (Mneina et al., 2018). Further, incorporation of CKD replacing/reducing cement resulting into lesser absorption of fine RHA particles along with low trapping of water (Givi et al., 2010b; Mehta, 2004) made more free water available in the system to enhance bleeding. Thus, the factors increasing the bleeding has probably outweighed the generally known effect of higher surface area of finer CKD particles raising the water demand and lowering bleeding (Camiletti et al., 2013). Katz and Kovler (2004) have also observed higher bleeding with use of finer and inert asphalt dust in the CLSM mix against an expected reduced bleeding due to its higher fineness. High bleeding level of around 9 % has earlier been observed for excavatable CLSM (Razak et al., 2009; Tikalsky et al., 2004) which is attributable to use of more water for flowability and less cement to control the strength for excavatability. CKD mixes with higher bleeding suggest using lesser water and make using CKD cost-effective and sustainable in this respect.

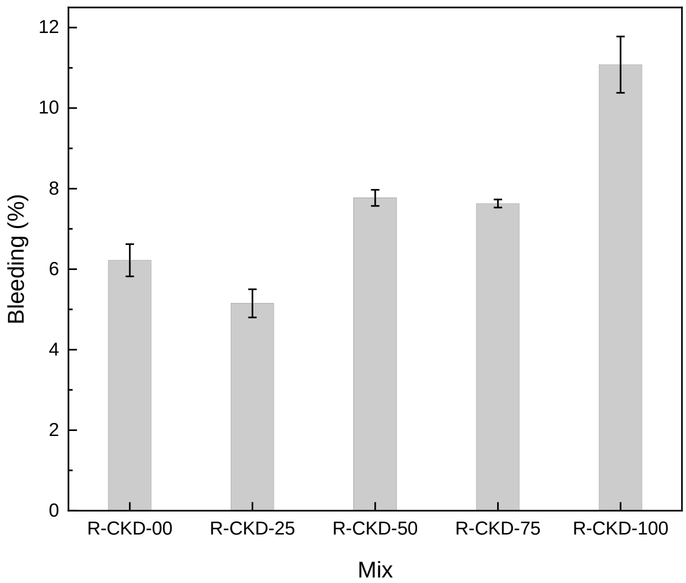


Figure 4.15 Bleeding of Group-2 CLSM mixes

4.3.4 Setting Time

CLSM is required to attain reasonable stiffness before being put in service. Appropriateness of CLSM stiffening for service has been examined by both penetration resistance (PR) as well as ball drop resistance methods. Setting time results with respect to PR and PR versus time graphs for the Group-2 mixes are presented at Table 4.5 and Figure 4.16. The results depicted that the time taken for attaining initial and final setting level increased with the progressive addition of CKD in CLSM mixes. Further, all the five CLSM mixes with

0-100 % CKD attained the initial setting level of PR=0.34 MPa in 12-190 hours. The initial setting time for the mixes with 0-75 % CKD were reasonable (47 hours) which increased significantly to 190 hours at 100 % CKD. However, only the mixes with 0, 25 and 50 % CKD could achieve the final setting level PR=2.76 MPa in 216, 255 and 598 hours. Final setting time for the mixes with 0-25 % CKD were close (215, 255 hours) which significantly increased to 598 hours for 50 % CKD.

The ball drop resistance results are presented in Table 4.5 and indentation diameter versus time curve for the mixes as per ball drop testing is shown at Figure 4.17. The results indicate that mix with 0 % CKD only could achieve sufficient stiffness for an indentation diameter of 76 mm after 1116 hours. However, mixes with 0- 50 % CKD could attain enough stiffness for a 100 mm diameter indentation that too at 265, 361 and 1031 hours. CLSM at 76 mm diameter indentation have attained enough stiffness that suit utility applications and at 100 mm diameter for pavement subgrade (ASTM D6024, 2016). The mixes with 75 % and 100 % CKD could not achieve enough strength to leave an indentation mark of even 100 mm diameter.

The RHA has been used as the only fine aggregate in the mixes and it has a pozzolanic character. Pozzolanicity of RHA depends upon amorphous content and fineness of particles. As received unprocessed RHA used in the study is not a fine material and therefore supposed to have very low pozzolanicity. Probably this aspect has not effected a change in setting behaviour of the CLSM mixes in Group-2. CKD addition by equivalent reduction of cement resulted in diminished hydration and pozzolanic reaction along with lower strength at a given age. Additionally, high loss on ignition (LOI) of CKD also resulted a reduced strength as CKD with high LOI having more bound water in chemical structure along with less CaO, interferes with hydration process (Adaska and Taubert, 2008). High SO_3 content in the CKD compared to cement might also have retarded the setting of the CLSM (Pierce and Williams, 2012). High bleeding at 5.15 to 11.08 % of the CLSM mixes also reflected increased setting and hardening time (Zhang et al., 2018).

Group-2 used RHA as the fine aggregate compared to SFS in Group-1. All the Group-1 mixes were able to achieve PR of 2.76 MPa but only mixes with up to 50% CKD were able to attain the final setting level of PR 2.76MPa. Also, in terms of ball drop resistance, only one mix with 0% CKD achieved stiffness equivalent to 76mm indentation diameter, whereas all Group-1 mixes attained the 76mm indentation level. Use of SFS proved better than RHA as aggregate in CLSM mixes in terms of load application suitability. Compared to Group-1 aggregate SFS with a very low absorption, the Group-2 aggregate RHA’s high porosity and associated high water requirement for achieving desired flowability probably caused the poor performance.

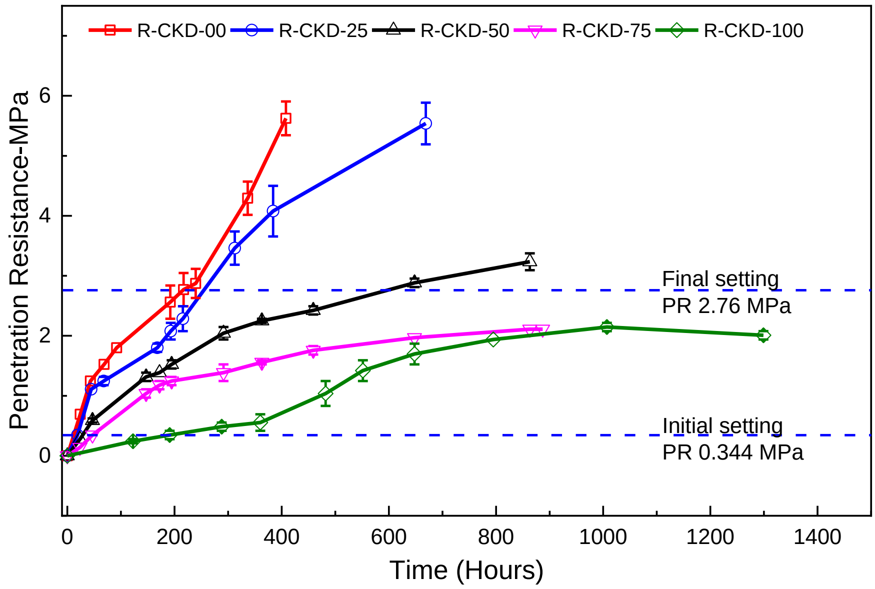


Figure 4.16 Setting time as per Penetration resistance Vs Time of Group-2 CLSM mixes

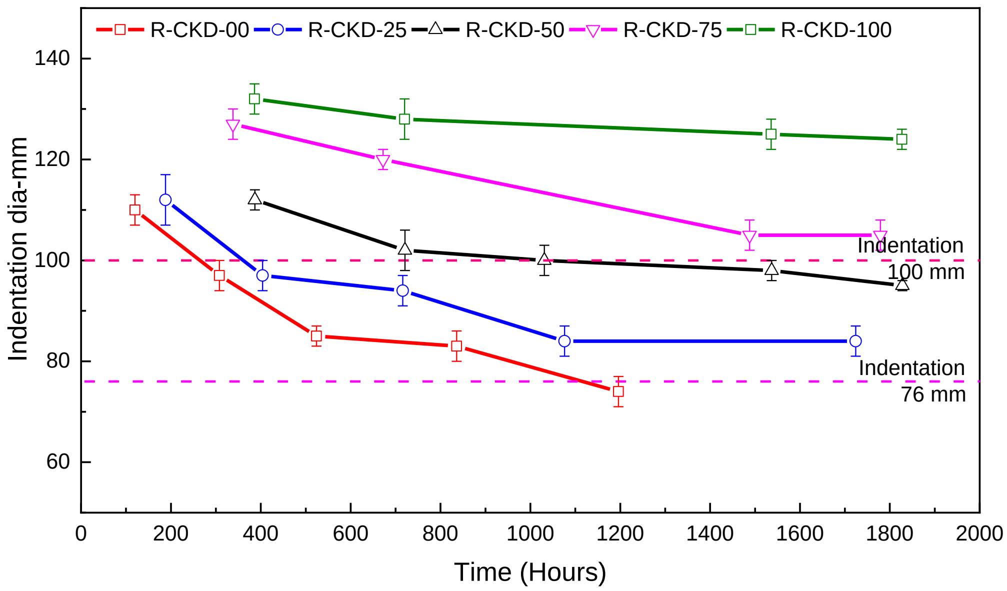


Figure 4.17 Setting time as per Ball drop indentation versus time of Group-2 CLSM mixes

The setting time by needle penetration and the ball drop procedures are positively correlated with respect to addition of CKD similarly as reported (Lachemi et al., 2008). Keeping in view the stiffening of CLSM as per PR and ball drop procedure, CLSM mixes, with CKD up to 50 % will suit backfill application for which early strength/setting time aren't critical like non-structural and excavatable CLSM (Ling et al., 2018a). R-CKD-00 achieving 76 mm indentation suited utility trench backfill while R-CKD-25 and R-CKD-50 having achieved an indentation 100 mm may also suit as pavement subgrade (ACI 229R, 1999). Setting times of the CLSMs using CKD, RHA were quite high, use of richer mix with higher binder content or CKD with low LOI, high reactive calcium can potentially reduce the setting time along with enabling high CKD mixes to achieve desirable stiffness level.

Table 4.6 Hardened sate properties of Group-2 CLSM mixes

Mix	Unit wt. (As-unmoulded AU) 28 days (kg/m^3)	Unit wt. (OD kg/m^3) and (% age of AU Weight)	Water Absorption	Unconfined Compressive strength: 'UCCS' (MPa)			Drying shrinkage (%)				Permeability coefficient 'K' (cm/sec)
			(%)	28 days	56 days	91 days	25 days	53 days	81 days	193 days	
R-CKD-00	1073.8	584.4 (54.42%)	101.4	0.309	0.443	0.476	0.0777	0.0933	0.1138	0.1445	8.13x10^{-4}
R-CKD-25	1085.2	569.3 (52.43%)	109.3	0.208	0.236	0.262	0.0035	0.0133	0.0329	0.0520	1.30x10^{-3}
R-CKD-50	1053.8	417.6 (39.62%)	186.1	0.118	0.122	0.140	0.0327	0.0693	0.0833	0.0897	2.32x10^{-3}
R-CKD-75	1079.2	416.3 (38.57%)	175.1	0.067	0.068	0.069	0.0585	0.0814	0.0863	0.0884	1.63x10^{-3}
R-CKD-100	1177.7	483.7 (41.07%)	x	0.032	0.044	0.047	0.0038	0.0060	0.0055	0.0203	x

'x' – The specimen crumbled during immersion for saturation in water due to inadequate binding

4.3.5 Hardened state unit weight and water absorption

The unit weights of hardened CLSM mixes at 28 days in as-unmolded (AU) and in oven-dried (OD) state are presented in Table 4.6 and Figure 4.18. The 28 days unit weight of all the CLSM mixes ranging between 1054-1178 kg/m^3 are lesser than the unit weight of 1650 kg/m^3 for a compacted earth fill or normal CLSM (Wu and Tsai, 2008). The low unit weight of the CLSM mixes is attributed to use of RHA as the fine aggregate. Nataraja and Nalanda, (2008) also observed that the unit weight of CLSM majorly depended upon unit weight of the material used as fine aggregate. Further, the OD unit weight of the CLSM ranging between 416-585 kg/m^3 was substantially less than the AU unit weight, which was attributed to loss of moisture by oven-drying (ACI 229R, 1999). Nataraja and Nalanda, (2008) also reported very low dry densities of around 899-966 kg/m^3 for CLSM having cement, RHA mixtures (1:17.5, 1:10 and 1:5). Comparatively higher dry densities in the said study were possibly due to use of pulverized RHA resulting into more dense mix compared to use of unprocessed/unground RHA in present Group-2 study. The minimum AU unit weight observed for R-CKD-00 and highest for R-CKD-100 mix showed the trend that addition of CKD in the mix increased the unit weight (AU).

Addition of CKD leading to higher bleeding, and more settlement/packing of the mix resulted in higher hardened unit weight. Similar variation in AU unit weight of CLSM mixes related to bleeding was observed in Group-1 mixes showing minimum value for 0 % CKD and maximum for 100 % CKD mix. In Group-1 mixes with spent foundry sand as the fine aggregate, the OD weight also followed the trend of AU unit weight. However, in Group-2 CLSM mixes presented a reverse trend of OD unit weight with maximum value for R-CKD-00 and minimum value for R-CKD-100. Similar trend is also seen in the study by Nataraja and Nalanda, (2008), wherein cement:RHA mixes of 1:17.5, 1:10 and 1:5 showed hardened state saturated densities of 1389, 1372 and 1365 kg/m^3 with highest for the less cement or poorer mix and the dry densities of 899, 932 and 966 kg/m^3 were lower for poorer mixes. For explanation, it is to be noted that the as-unmolded hardened CLSM also has a lot of moisture held up in porous structure of the hardened mix. Further, fine aggregate RHA is pozzolanic material and of highly porous vesicular/cellular particle structure (Rukzon et al., 2009). The RHA by providing more nucleation sites for deposition of hydration and pozzolanic reaction products in a cement matrix results into reduced permeability/porosity (Abolhasani et al., 2022; Feng et al., 2004; Givi et al., 2010a; Rukzon et al., 2009). The addition of CKD reduces cement content making the mix poorer which would lead to reduced hydration/pozzolanic reaction and result into more porosity in hardened CLSM. Further, the loss of the moisture on drying from more porous structure possibly resulted into lesser OD unit weight. Use of RHA and CKD would be beneficial as the resulting low density CLSM are suitable for application as insulation and isolation fill and also for weak soil conditions requiring minimum weight from fill (ACI 229R, 1999) in addition to economical design of to-be-embedded utility elements and save raw materials.

The water absorption potential for the four mixes could be examined as mix with 100 % CKD crumbled when submerged in water for saturating. This was due to development of inadequate binding between the mix constituents. Water absorption of the CLSM mixes was very high between 101-186 % attributable to use of highly porous unprocessed RHA as the only fine aggregate, low cement content and requirement of very high water/binder ratio (8.25) for desired high flowability (250 mm). The water absorption results presented in Table 4.6 and Figure 4.18 show an increased water absorption for addition of CKD in the CLSM. Water absorption is related to porosity and addition of CKD in the mix increased the porosity in hardened CLSM as discussed above. Therefore, increased water absorption is attributable to rising porosity with addition of CKD. Nataraja and Nalanda (2008) have also reported around 50 % water absorption for CLSM mixes even with use of pulverized RHA as fine aggregate compared to unprocessed RHA in current study.

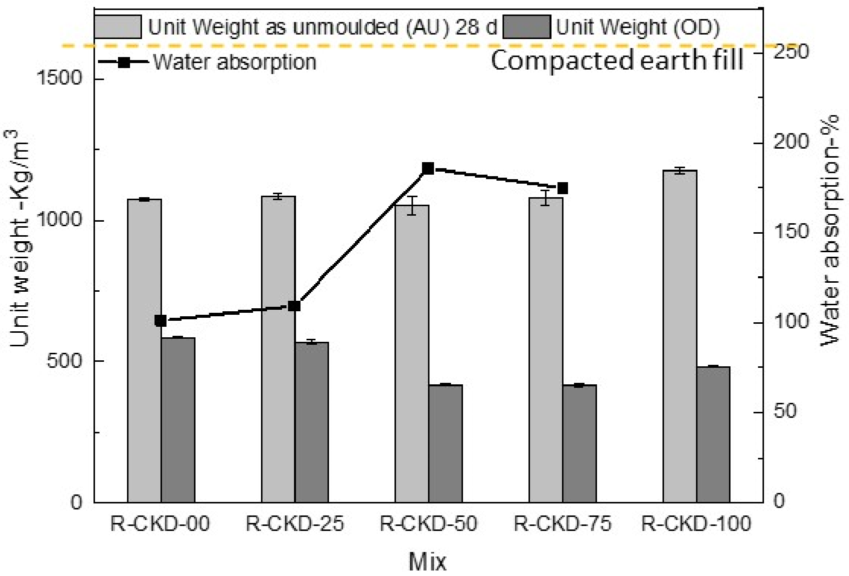


Figure 4.18 Hardened state Unit weight of Group-2 CLSM mixes

4.3.6 Unconfined compressive strength and California bearing ratio (CBR)

Unconfined compressive strength (UCCS) of the Group-2 CLSM mixes, as presented in Table 4.6 and Figure 4.19, are between 0.03-0.31 MPa, 0.04-0.44 MPa and 0.05-0.48 MPa for curing age of 28 days, 56 days and 91 days respectively. Also, the strength has gained over the duration of 91 days and the rate of strength gain over age decreased at higher CKD addition. Addition of CKD as replacement of cement in CLSMs has resulted into decreased UCCS. Similar to Group-1, CKD addition in CLSM caused a reduced strength of Group-2 CLSM for various reasons like reduced cement reducing major strength contributors like alite and belite etc. (C_3S, C_2S) in the system, higher content of CKD with high LOI (22 %) and SO_3 (6 %) (Adaska and Taubert, 2008; Pierce and Williams, 2012) and increasing paste volume ratio (PVR) (Alizadeh, 2019; Kolias and Georgiou, 2005). Nataraja and Nalanda, (2008) used pulverized RHA in CLSMs mixes with cement:RHA ratios of 1:5 and observed 28 days compressive strengths of 0.49 MPa and 60 days strength of 0.50 MPa. The UCCS 0.31 MPa of R-CKD-00, the richer cement:RHA ratio 1:3 mix in Group-2 study, was lesser possibly due to use of unprocessed RHA as fine aggregate. Pozzolanicity of RHA depends upon amorphous content and fineness of particles. As received unprocessed RHA used in the Group-2 study is not a fine material and therefore supposed to have very low pozzolanicity compared to pulverized RHA used by Nataraja and Nalanda, (2008). Low pozzolanicity of unprocessed RHA possibly resulted in less strength. Further the significant strength gain (0.31 to 0.44 MPa) from 28 days to 56 days seen in Group-2 study compared to almost no change (0.49 to 0.50 MPa) seen in Nataraja and Nalanda (2008) study was owed to richer mix with higher cement.

Long term strength of CLSM is important since it affects its future-excavatability (ACI 229R, 1999; Lachemi et al., 2010). All the CLSM mixes attained maximum long-term strength of 0.48 MPa less than 0.70 MPa were excavatable either manually or with conventional equipment.

In terms of application all the CLSM mixes had 28 days UCCS less than 0.50 MPa and were suitable for general backfill applications like filling the void and abandoned underground structures where early setting also is not critical (Ling et al., 2018a). Excavatability of CLSM mixes manually/with conventional digging equipment make them sustainable for consuming less energy compared to a mechanical equipment required for any structural mix (UCCS > 0.70 MPa). Considering the setting time along with sustainability i.e., maximum utilization of by-products, CLSM mix R-CKD-50 shall be best.

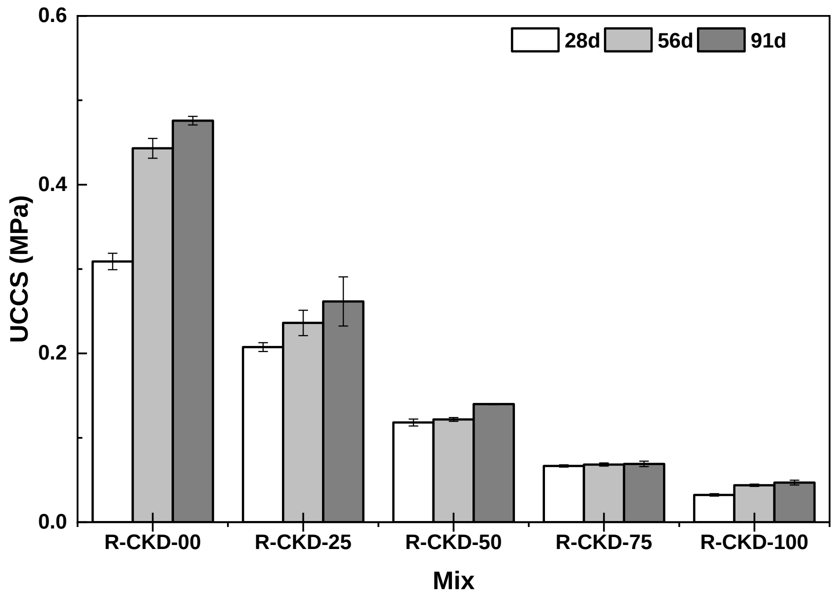


Figure 4.19 Unconfined compressive strength (UCCS) of Group-2 CLSM mixes

California bearing ratio (CBR) of the CLSM was proposed to be conducted at the age of ball drop resistance time for 76 mm indentation. Only the mix with 0 % CKD in Group-2 could achieve enough stiffness required for 76 mm indentation on the CLSM surface. CBR value of the R-CKD-00 was evaluated as 15.8 %. The CLSM mixes R-CKD-00 has CBR between 10-25 % and has an allowable bearing pressure equivalent to a well compacted sand (Knapton, 1999).

4.3.7 Drying shrinkage

Drying shrinkage versus time graphs showing development of shrinkage in the CLSM mixes are presented at Figure 4.20 and shrinkage at 25, 53, 81 and 193 days of drying is presented in Table 4.6. The shrinkage increased with time of drying across all the CLSM mixes. Also, the shrinkage development was at faster rate up to the initial period of 25 days and slowed down thereafter and attained the ultimate shrinkage level at around 180 days. Similar pattern for shrinkage development at higher rate initially has also been reported previously (Vardhan et al., 2019). Ultimate shrinkage for the CLSM mixes ranged between 0.0203 - 0.1445 %. Ultimate shrinkage of the level of 0.25% for CLSM with CKD have been reported (Lachemi et al., 2008). Comparison of the results showed maximum shrinkage for the mix R-CKD-00 i.e., 100 % cement and minimum for R-CKD-100 with 100 % CKD. Also, R-CKD-25 underwent less ultimate shrinkage (0.052 %) than both R-CKD-50 (0.089 %) and R-CKD-75 (0.088 %) attaining almost same level of ultimate shrinkage.

Comparing the results, it was seen that CKD addition in CLSM resulted into lowered ultimate shrinkage. This was opposite to the trend of enhanced shrinkage with the addition of CKD observed in previous studies (Katz and Kovler, 2004; Lachemi et al., 2008). Even in Group-1 CLSM addition of CKD enhanced shrinkage. These studies used spent foundry, crushed sand and natural sand as fine aggregate materials along with CKD. The mix constituents, both binder as well as and fine aggregate, CKD and RHA affected the net shrinkage results for the CLSM in different ways. Generally, the addition of CKD would potentially enhance shrinkage due to concurrent effects like finer CKD particles retaining more water and drying from the bulk (Katz and Kovler, 2004), dilution resulting into lesser cement and hydration products along with diminished disruption of capillary channels, availability of higher free water for evaporation (Aboutabikh et al., 2016) and filling i.e., finer CKD refining pore structure leading to more internal strains (Aboutabikh et al., 2016; Mneina et al., 2018). Addition of CKD also reduced cement in the mix and with less hydration products porosity would increase. Moreover, the fine aggregate RHA in the mix being highly porous due to its vesicular structure acted as internal reservoir. Loss of moisture during drying was compensated by internal adjustment effect facilitated by re-distribution of water in porous structure of RHA (de Sensale et al., 2008; Wang et al., 2021) which reduced shrinkage. The internal curing effect of RHA had more influence upon shrinkage in Group-2 study. Additionally, the mixes with

CKD shall also be volumetrically more stable on account of less ultimate shrinkage than 100 % OPC mix. It is also pertinent to note that shrinkage and related cracking do not affect the performance of CLSM (ACI 229R, 1999). It needs to be mentioned that the specimen with high replacement levels of CKD were very fragile and required to be handled with care during testing to avoid crumbling.

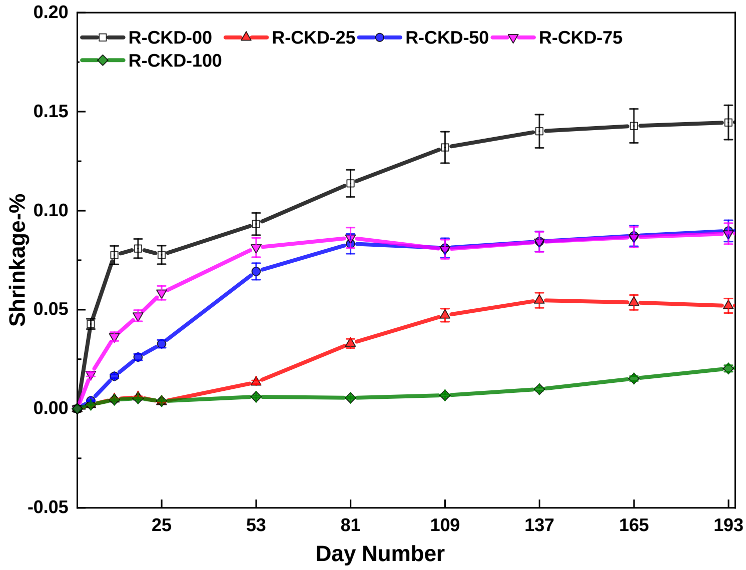


Figure 4.20 Drying shrinkage versus Time of Group-2 CLSM mixes

4.3.8 Permeability

Coefficient of permeability (K) of the four CLSM mixes with 0 % to 75 % CKD are presented at Table 4.6 and Fig. 4.21. The permeability values range between 8.13×10^{-4} to 2.32×10^{-3} cm/sec. Permeability of the fifth mix R-CKD-100 could not be examined since the specimen crumbled when immersed in water for saturating the same prior to testing due to insufficient binding between the constituents. With minimum value for 0 % CKD mix, the addition of CKD resulted in increased permeability. This was opposite to the previously observed trend of reduction in permeability due to addition of CKD as replacement of cement (Al-Harthy et al., 2003). Also, similar reduction of permeability was observed in Group-1 CLSM mixes. As a matter of fact, both binder and fine aggregate have a role in permeability of the mix. In the said studies natural sand and spent foundry sand were used as fine aggregate along with CKD as binder. Finer CKD particles has the potential to reduce the average grain size of the constituents, fill voids/refine the pore structure and reduce permeability (Al-Harthy et al., 2003; Dillip Kumar Bera et al., 2015; Terzaghi et al., 1996). In Group-2 study by-products RHA is the fine aggregate and CKD as binder. RHA has very high porosity owing to its vesicular nature and supposed to enhance mix porosity and permeability (Venkatanarayanan and Rangaraju, 2015). Further, addition of CKD in the CLSM also reduced cement content, diminished the hydration and pozzolanic activity that rendered a more porous/permeable CLSM mix. Influence of RHA dominated the permeability of the CLSM mixes and for 75 % CKD effect of refinement of the pore structure caused slight permeability reduction.

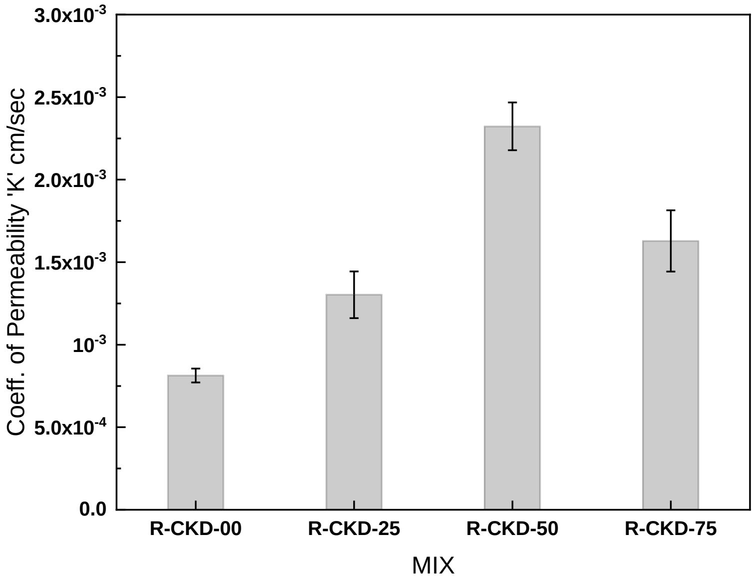


Figure 4.21 Coefficient of Permeability 'K' of Group-2 CLSM mixes

The coefficient of permeability of the mixes in Group-2 study is around 10^{-4} -10^{-3} cm/sec, which is around the typical range for an excavatable CLSM, compacted granular fills, and clean sand with good draining ability (ACI 229R, 1999; Terzaghi et al., 1996). The permeability coefficient were around 2.38×10^{-5} cm/sec for CLSMs using natural sand as fine aggregate as reported by Lachemi et al. (2008) and between 10.3×10^{-4} - 2.39×10^{-4} cm/sec for CLSM using spent foundry sand as fine aggregate in Group-1. The higher coefficient of permeability of mixes with CKD at around 2.32×10^{-3} cm/sec in Group-2 mixes is due to use of highly porous RHA compared to solid aggregates used in preceding studies. Crumbling of specimen during immersion in water may be avoided by using at least some cement content along with high CKD content instead of 100 % replacement. However, use of CKD having low LOI with reactive lime may allow 100 % replacement of cement without specimen crumbling in water.

4.3.9 Mineral phase identification (XRD) and microstructure (FESEM, EDS)

X-ray diffraction scan for identification of the mineral phases in CLSM presented at Figure 4.22 showed presence of crystallized phases of quartz (Q) and calcite (C) with minor presence of ettringite (E), gismondine (Gs) and gypsum (G). Calcium hydroxide phase was not observed due to its possible consumption in pozzolanic reaction owed to presence of major proportion of RHA (Rahman et al., 2016; Rêgo et al., 2015). Phases of ettringite and gismondine in 28 day CLSM represented an ongoing strength activity by hydration process in the CLSM mixes (Do et al., 2019). This is reflected by higher unconfined compressive strength for the CLSM mixes beyond 28 days. Presence of ettringite in the 100 % CKD mix represented some cementing behavior by CKD. However, the same might not be significant enough since the 100 % CKD specimen crumbled during immersion for saturating the same before the permeability testing. Presence of gypsum phase in CLSM at 28 days show insufficient reactants in the system and reflect an incomplete pozzolanic hydration process (Devaraj et al., 2023; Do et al., 2019). The phase composition for all the CLSM mixes with varying CKD/Cement proportions remained similar i.e., without any qualitative change, which meant that the CKD used was almost inert. Similar observations were also reported previously (Vardhan et al., 2015).

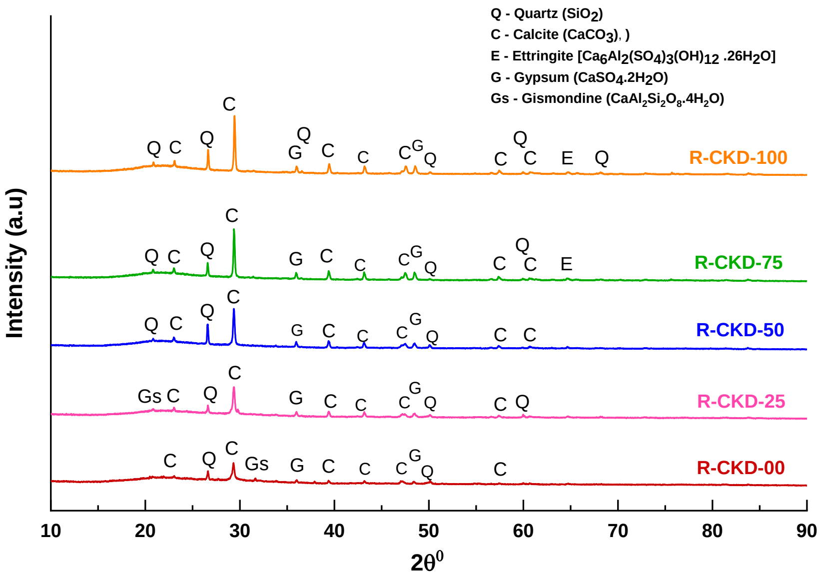
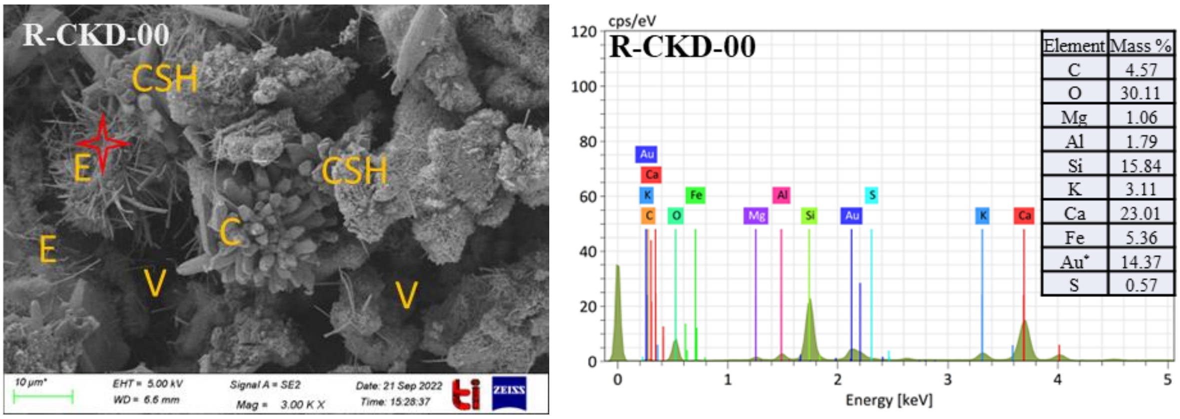
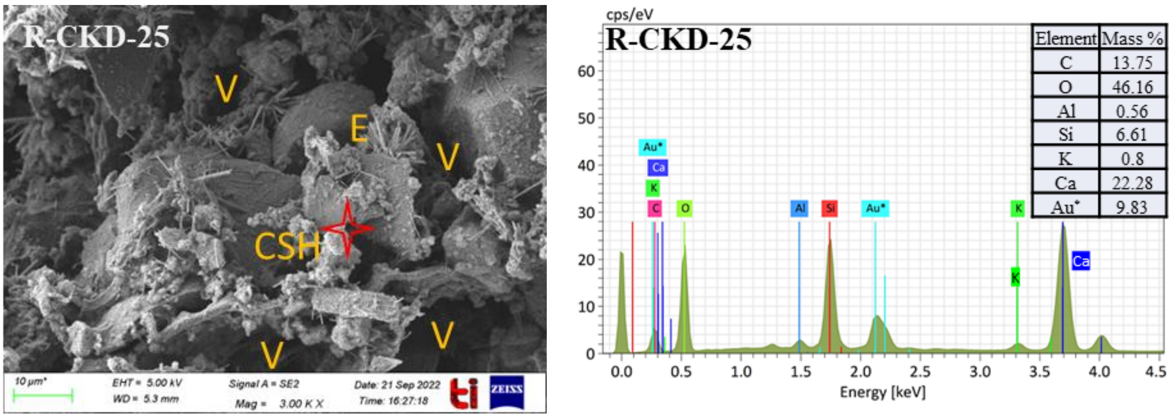


Figure 4.22 XRD scan of Group-2 CLSM mixes

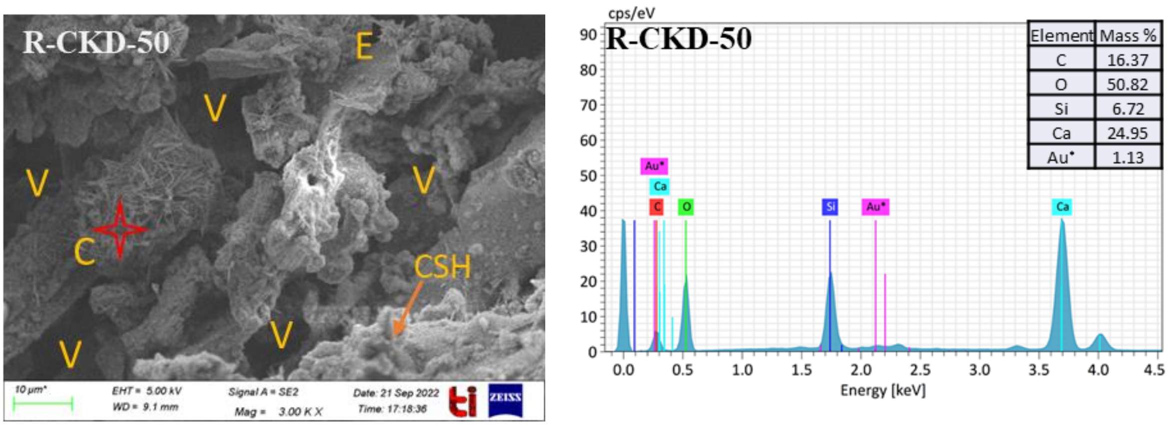
Field emission scanning electron microscopy (FE-SEM) and energy dispersive spectroscopy (EDS) of the Group-2 CLSM are presented in Figure 4.23 (a)-(e). Phases such as calcite (C), calcium silicate hydrate (CSH) and ettringite (E) were seen in FE-SEM images of CLSM mixes with 0-75% CKD i.e., cement up to 25%. Calcium hydroxide (CH) phases were not observed probably due to its pozzolanic reaction in presence of RHA to make CSH gel phases. Mix with 100% CKD shows only unreacted particles of the constituents further indicating the used CKD to be almost inert. Crumbling of 100 % CKD mix specimen during immersion in water for hardened unit weight and permeability testing also reflected inadequate binding in mix constituents for no/insignificant hydration activity. Any binding seen in 100 % CKD mix is attributed to insignificant hydration process or interlocking effect within mix particles similarly as in Group-1 mixes. Increased voids (V) in the CLSM with higher CKD validated increased permeability results.



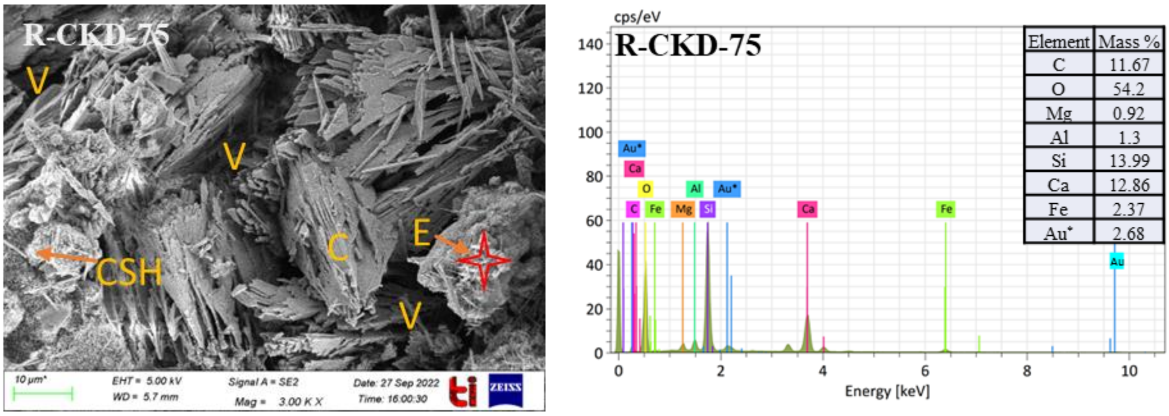
(a)



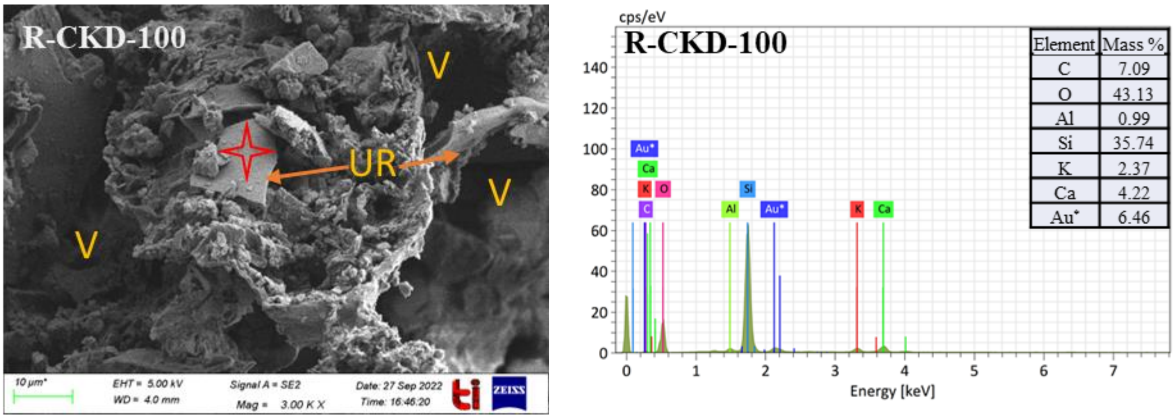
(b)



(c)



(d)



(e)

Figure 4.23 FE-SEM and EDS image of Group-2 CLSM mixes (a) R-CKD-00; (b) R-CKD-25 (c) R-CKD-50 (d) R-CKD-75 and (e) R-CKD-100

The major reactants, namely Si, Al and Ca along with Si/Al ratios in the chemical composition of the CLSM mixes examined through EDS analysis are presented at Table 4.7. The Si/Al ratios for the mixes show a general rising trend among majority of Si/Al ratio of mixes with addition of 0-100 % CKD. The diminishing UCCS of CLSM with addition of CKD are negatively correlated with their rising Si/Al ratio similarly as reported previously (Chindaprasirt et al., 2009; Ho et al., 2022; Hwang et al., 2017).

Table 4.7 EDS analysis of Group-2 CLSM mixes

Mix	Average quantity by mass (%)			Si/Al
	Si	Al	Ca	
R-CKD-00	24.42	1.03	12.83	23.70
R-CKD-25	23.04	0.87	9.85	26.48
R-CKD-50	25.04	0.88	11.99	28.45
R-CKD-75	19.60	0.97	19.05	20.20
R-CKD-100	24.09	0.68	5.82	35.42

4.4 PROPERTIES OF THE GROUP-3 CLSM MIXES *(Cement + Cement Kiln Dust as binders, Spent foundry sand + unprocessed Rice Husk Ash as fine aggregates)*

Five mix proportions were considered in this group for experimentation. Spent foundry sand and rice husk ash both in 50:50 by weight ratio were used as fine aggregate. OPC and CKD both were taken as binders. The binder to aggregate ratio was 1:3 and five CLSM mixes were prepared for Group-3 study with CKD replacing cement at five levels i.e., 0 %, 25 %, 50 %, 75 % and 100 %. The water content for the CLSM mixes was evaluated for achieving a target flowability of around 200 mm as per (ASTM D6103, 2004). The constituents' proportioning for CLSM mixes Group-3 is presented at Table 3.13.

Characteristics of each CLSM mix in the fresh and the hardened state were examined by conducting various tests. Also, mineral phase examination, microstructural analysis, leachate toxicity and ecological analysis of the CLSM mixes was also done.

4.4.1 Flowability

Flowability of around 200 mm was targeted for the Group-3 CLSM mixes and w/b ratios were ascertained. Flowability along with w/b for the CLSM mixes is presented in Table 4.8 and Figure 4.24. Results show that with the addition of up to 75% CKD as replacement of OPC in the mixes, a marginally higher w/b is required to achieve the target flowability. However, for the mix with 100 % CKD i.e., no OPC, minimum w/b was required to achieve the desired flow. Initial higher water demand is possibly owing to increasing fineness (specific surface) of resulting binder blend for CKD being finer than OPC (Khanna, 2009; Marku et al., 2012). In mix with 100 % CKD i.e., with no cement no water would be engaged in hydration but solely be available for providing flowability and hence a reduced water requirement. Factors like increased packing by filling voids and the lubrication effect of inert CKD particles (Camiletti et al., 2013; Mneina et al., 2018), higher content of CKD causing wider particle size distribution of the binder and matrix (Hawkins et al., 2005) also potentially lowered the water demand for a given flow. Final water demand for any mix would be guided by the combined effect of the factors increasing and of those decreasing the demand. CKD mixes required water to binder ratio (w/b) in a narrow range (4.39-4.57) for 0-75 % CKD mixes and quite lesser (3.71) for 100% CKD mix. In terms of water content per cubic meter of the CLSM also (Table 3.13), mixes with 0-75 % CKD required almost same quantity and with 100 % CKD required lesser quantity.

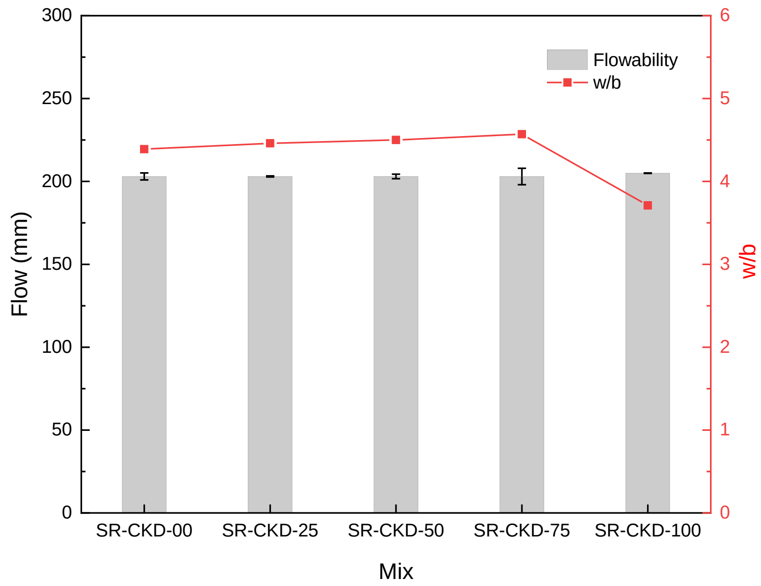


Figure 4.24 Flowability of Group-3 CLSM mixes

Table 4.8 Fresh state properties of Group-3 CLSM mixes

Mix Designation	Fresh Unit weight kg/m^3	Flow (mm)	Water to binder ratio (w/b)	Bleeding %	Initial Setting time at PR 0.344 MPa (hrs)	Final Setting time at PR 2.76 MPa (hrs)	Ball drop setting time at indentation dia-76 mm (hrs)
SR-CKD-00	1412.2	203	4.39	6.66	5.4	41.8	141.5
SR-CKD-25	1401.5	203	4.46	5.26	6.2	50.2	160.3
SR-CKD-50	1397.3	203	4.50	4.28	6.4	60.5	204.6
SR-CKD-75	1390.7	203	4.57	4.51	8.0	97.5	648
SR-CKD-100	1446.3	205	3.71	7.69	52.9	217.9	x

w-water; b-binder= (Cement +CKD); X-could not achieve 76mm indentation level

4.4.2 Fresh state unit weight

The fresh unit weight of the Group-3 CLSM mixes ranged between 1391-1446 kg/m^3 as presented in Table 4.8 and Figure 4.25. The values are in the range of 1360-1760 kg/m^3 specified for pond/basin ash CLSM but below the range 1840-2320 kg/m^3 for a normal CLSM (ACI 229R, 1999). Similar to Group-2, lower unit weight values of the Group-3 CLSM than a normal CLSM is due to use of low specific gravity materials (CKD and RHA) as major constituents. Comparison of unit weight of CLSM mixes indicated that unit weight reduced with addition of 0-75% CKD in replacement of OPC which was attributable to CKD's lower specific gravity than cement. However, the reduced water demand for 100 % CKD mix might have resulted into denser mix and a higher unit weight. Group-1 CLSM also showed similar variation in the fresh unit weight values. Similar reduction in unit weight owed to variation in specific gravity of constituents is also reported previously (Ahadzadeh Ghanad and Soliman, 2021; Lachemi et al., 2008; Mneina et al., 2018; Taha et al., 2007). Lighter CLSM used in a utility construction will be beneficial in terms of leaner design of utility elements, cost-effectiveness and sustainability. CLSM with lower fresh unit weight shall exert less lateral pressure behind basement walls or other such structures (ACI 229R, 1999). Therefore, use of by-products RHA and CKD is advantageous in reducing unit weight.

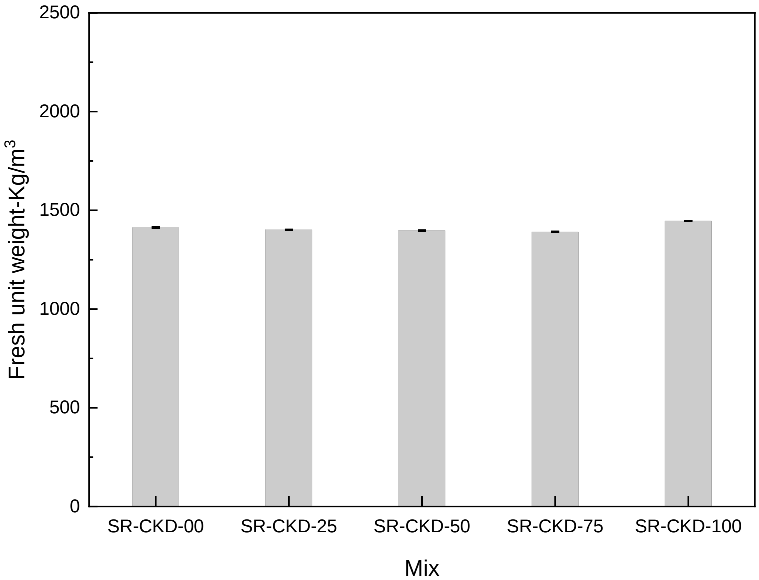


Figure 4.25 Fresh state Unit weight of Group-3 CLSM mixes

4.4.3 Bleeding

The bleeding results for the Group-3 CLSM mixes are presented in Table 4.8 and Figure 4.26. The bleeding values for the CLSM mixes with addition of 0 to 50 % CKD decreased from 6.66 % to 4.28 % followed by an increased bleeding with further increase in CKD. Initial drop in bleeding for CKD up to 50 % might be due to higher water demand resulting from increasing surface area (Katz and Kovler, 2004) by addition of finer CKD in the binder (OPC+CKD). When CKD increased further a lesser amount of water was required for the hydration of reduced cement content (Mneina et al., 2018) that overcame the higher water demand due to finer CKD particles and resulted an increased bleeding. Also addition of finer CKD resulting into wider particle size distribution of matrix leading to reduced water demand (Aiqin et al., 1999; Hawkins et al., 2005) and reduced cement with lesser absorption of fine RHA particles along with less trapping of water (Givi et al., 2010b; Mehta, 2004) made more free water available in the system that potentially enhanced bleeding. Except for mixes with 50-75 %

CKD, the bleeding values were above the desirable 5 % value for practical applications (Gabr and Bowders, 2000; Park et al., 2017; Zhang et al., 2018). However, higher bleeding value of 7-9 % have been reported for excavatable CLSM earlier also (Razak et al., 2009; Tikalsky et al., 2004). Requirement of more water for flow and low cement content to control strength development for an excavatable CLSM results in higher bleeding.

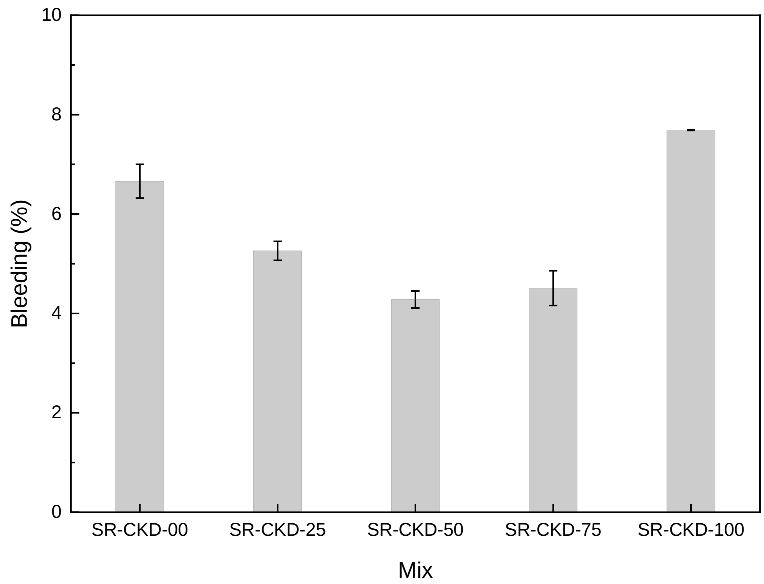


Figure 4.26 Bleeding of Group-3 CLSM mixes

4.4.4 Setting time

The setting time results as per penetration resistance (PR) and ball drop resistance are presented in Table 4.8. PR versus time curves for the CLSM mixes are shown at Figure 4.27 and ball drop indentation diameter versus time graph at Figure 4.8. Setting time (PR) results for the Group-3 CLSM mixes depicting initial setting time (5.4-53 hours) for PR=0.34 MPa and final setting time (42-218 hours) for PR=2.76 MPa showed that the setting time increased with addition of CKD as replacement of cement. Mixes with up to 0-50 % CKD showed very close final setting time (60 hours) and much higher (98 hours) for 75 % CKD mix. Achievement of required PR with 100 % cement replacement showed that CLSM mix entirely comprising of industrial by-products can be envisaged. Such CLSM can suit situations where setting time was not critical such as in general backfill. Initial and final setting time reduced from 53 to 8 hours and 218 to 98 hours respectively for addition of even 25 % OPC while comparing mixes with 100 % CKD and 75 % CKD. Therefore, the setting times can be controlled to reasonable levels even by adding small proportion of OPC.

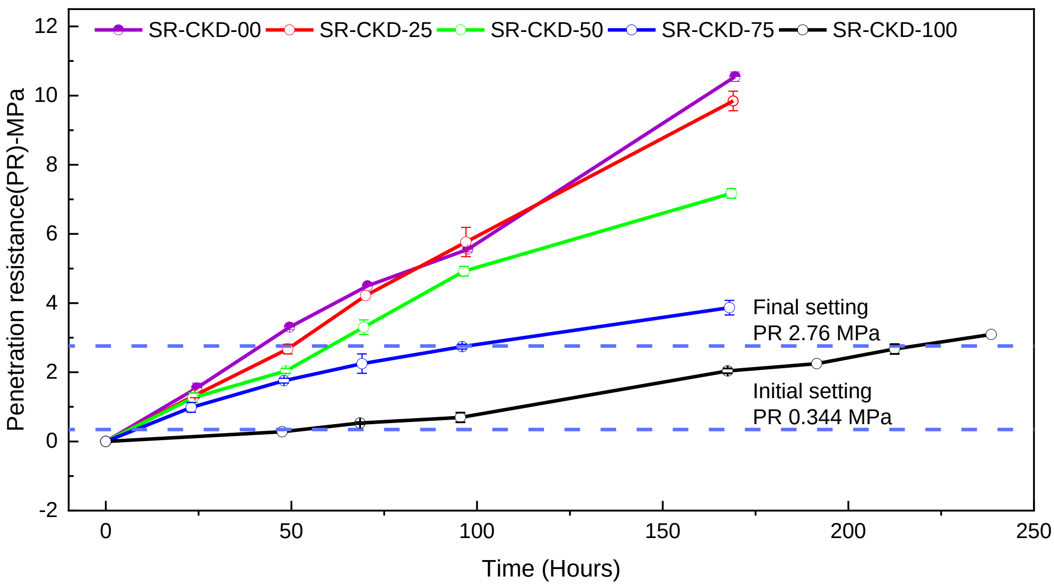


Figure 4.27 Setting time as per Penetration resistance Vs Time of Group-3 CLSM mixes

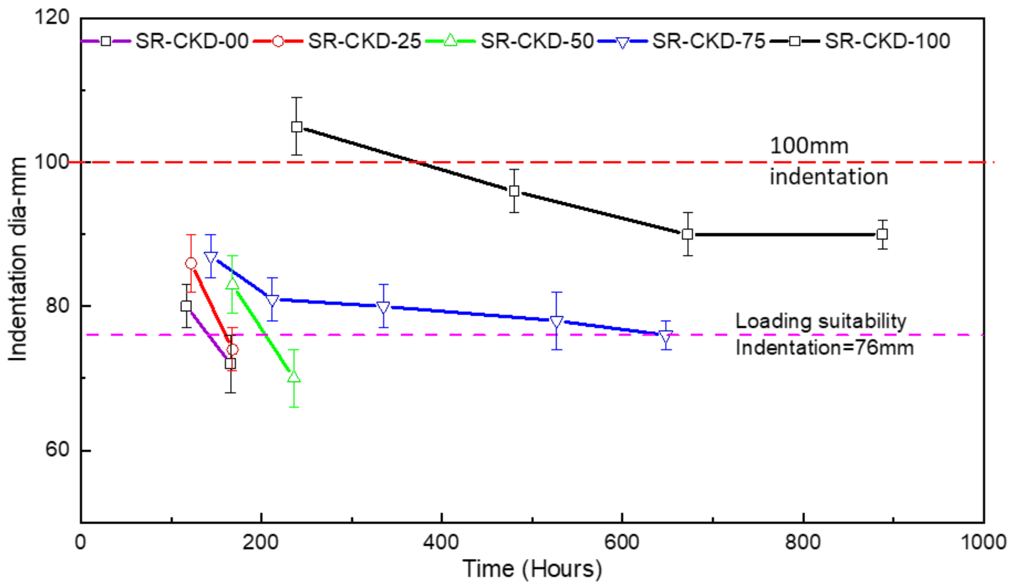


Figure 4.28 Setting time as per Ball drop indentation Vs Time of Group-3 CLSM mixes

Setting times for the indentation diameter of 76 mm through ball drop resistance procedure were between 142-648 hours for the first four mixes with 0 to 75 % CKD. The mix with 100 % CKD could not achieve enough strength to leave an indentation mark of 76 mm diameter or lesser. CLSM mixes with up to 50 % CKD achieved the desired setting level in reasonably short time (204 hours) whereas mix with CKD 75 % achieved it after quite longer period (648 hours). However, the mix with 100% CKD could achieve stiffness level for 100mm indentation suitable for pavement subgrade in 373 hours.

SFS and RHA constitute as fine aggregate in the CLSM with latter having a pozzolanic nature. It is to be noted that level of setting of any CLSM is related to achievement of strength at any particular age. Similarly as in the case of Group-1 and Group-2 mixes, the factors adversely affecting the strength such as reduction of cement due to replacement by CKD resulting in diminished hydration/pozzolanic reaction, high LOI (Adaska and Taubert, 2008), higher SO_3 in CKD (Pierce and Williams, 2012) and inert nature of CKD (Katz and Kovler, 2004) prolonged the setting times.

Except mix with 100 % CKD (SR-CKD-100), all CLSM mixes showed reasonable final setting time to attain PR 2.76 MPa and shall be good for backfill application requiring early setting, strength like non-structural excavatable fills e.g. underground pipe lines, conduit bedding, roadway trench etc. (Ling et al., 2018a). However, mix SR-CKD-100 shall be suitable for general backfill applications like void filling, abandoned underground structures etc. since early setting was not-critical for such applications. In terms of ball drop resistance, mixes with up to 75 % CKD, having achieved sufficient strength to allow 76 mm indentation, shall also be suitable for utility applications like trench backfill.

4.4.5 Hardened state Unit weight and water absorption

The unit weight of hardened CLSM mixes at 28 days in as-unmolded (AU) are in the range of 1005-1244 kg/m^3 and in oven-dried (OD) state 661-853 kg/m^3. The results are depicted in Table 4.9 and Figure 4.29. AU unit weight lesser than unit weight 1650 kg/m^3 of a compacted earth fill. The OD unit weight is notably lesser than AU unit weight owed to moisture loss during oven drying (ACI 229R, 1999). Results also indicate that both AU and OD unit weights respectively decreased from 1243 to 1005 kg/m^3 and 737 to 661 kg/m^3 with the progressive use of CKD as replacement of OPC till 75% level. This was followed by the increased AU and OD unit weight of 1149 and 853 kg/m^3 at 100% level. The trend was opposite to the trend seen in Group-1 and Group-2 where higher AU unit weight was witnessed for mixes with higher CKD. Higher AU unit weight in Group-1 and Group-2 was attributed to addition of CKD leading to higher bleeding and more settlement/packing of the mix resulting into higher hardened unit weight. Accordingly, addition of 0-75 % CKD and related reduced bleeding in Group-3 mixes rendered less dense mixes and related lowering AU unit weight. Additionally, use of lesser specific gravity material (CKD) in replacement for a higher specific gravity material (OPC) has also caused a reduced unit weight. However, the higher unit weight for the mix with 100 % CKD was a reflection of higher bleeding causing denser packing of the mix by the same principle.

Addition of CKD causing reduction of the OD unit weight of Group-3 mixes followed the trend of Group-2 mixes where poorer mixes i.e., with higher CKD (less cement) showed lower OD unit weight. The progressive increase in CKD with equivalent reduction of cement in the matrix reduced the hydration, pozzolanic reactions products and made CLSM more porous with lesser unit weight. Use of RHA and CKD has resulted in to CLSM with low density which are suitable for application as insulation and isolation fill and also appropriate for weak soil conditions that need minimum weight from fill (ACI 229R, 1999). The low unit weight of CLSM backfill would lead to economical design of to-be-embedded utility elements like pipes etc.

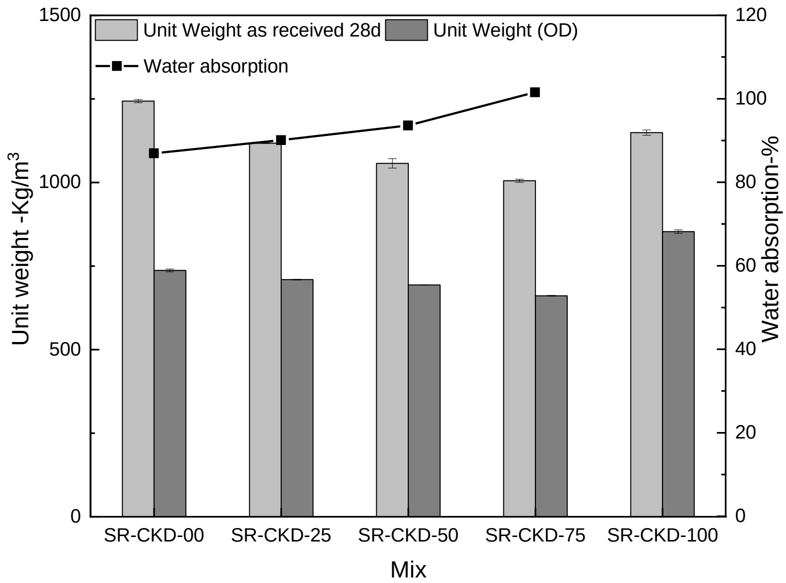


Figure 4.29 Hardened state Unit weight of Group-3 CLSM mixes

The water absorption potential for the four mixes were examined. The mix with 100 % CKD crumbled when submerged in water on saturating due to inadequate binding between the mix constituents. Similar to Group-2 CLSM, high water absorption values for Group-3 CLSM mixes between 86.9-101.5 % was also attributed to use of highly porous unprocessed RHA as one of the fine aggregates, low cement content and high water/binder ratio. Increased water absorption for addition of CKD presented in Table 4.9 and Figure 4.29 is related to an increased porosity in hardened CLSM as discussed above.

Table 4.9 Hardened state properties of Group-3 CLSM mixes

Mix	Unit wt. (As-unmoulded 28 days) (kg/m³)	Unit wt. (Oven-dried, OD) (kg/m³), (% of AU)	Water absorption (%)	Unconfined Compressive strength: 'UCCS' (MPa)			CBR at ball drop setting time (%)	Drying shrinkage (%)			Permeability coefficient 'K' (cm/sec)
				28 days	56 days	91 days		25 days	53 days	81 days	
SR-CKD-00	1243.5	737.1 (59.2%)	86.9	1.03	0.90	0.89	20.3	0.1398	0.2345	0.2548	1.29×10^{-4}
SR-CKD-25	1117.5	709.6 (63.5%)	90.1	0.75	0.63	0.57	17.5	0.1485	0.2121	0.2193	1.32×10^{-4}
SR-CKD-50	1057.3	693.5 (65.6%)	93.6	0.35	0.37	0.32	13.4	0.1328	0.1686	0.1775	2.55×10^{-4}
SR-CKD-75	1005.2	661.3 (65.8%)	101.5	0.12	0.10	0.07	7.7	0.1099	0.1231	0.1170	6.13×10^{-4}
SR-CKD-100	1149.3	853.1 (74.2%)	x	0.05	0.11	0.11	8.6[xx]	0.0144	0.0240	0.0262	[x]

[x] Specimen crumbled during immersion in water for saturation, test not possible. [xx] CBR at 28 days

4.4.6 Unconfined compressive strength

The UCCS of Group-3 CLSM mixes was evaluated at 28 days, 56 days and 91 days, and the results are presented at Table 4.9 and Figure 4.30. The UCCS of CLSM mixes at above three curing ages respectively ranged between 0.05-1.03 MPa, 0.10-0.90 MPa and 0.07-0.89 MPa. Results also depicted that UCCS decreased with increased addition of CKD as replacement of OPC, irrespective of the testing age. This trend was similar to Group-1 and Group-2. The factors like addition of CKD resulting into reduced cement with reduction of strength reactants like alite and belite etc. (Najim et al., 2014), high LOI CKD interfering with the hydration process (Adaska and Taubert, 2008), higher PVR resulting into low crack tortuosity (Alizadeh, 2019; Kolias and Georgiou, 2005) resulted into a reduced strength. Another prominent feature of UCCS of the CLSM was that some of the mixes prominently presented a reduced long term (at 56 days and 91 days) UCCS compared to 28 days. This was in contradiction with the general trend in many past studies depicting an increase in strength with age (Alizadeh, 2019; Katz and Kovler, 2004; Park et al., 2017). The reduced strength at later age could be due to curing in the air resulting into non-availability of sufficient internal moisture for hydration (Sajedi and Razak, 2011). Similar reduction in strength of CLSM mixes that were air cured is reported by Taha et al. (2007). Lee et al. (2013) has further linked the reduction in strength to possible evolution of cracking by drying shrinkage.

In terms of excavatability, all the developed mixes have 91 days UCCS less than 2.1 MPa and therefore shall be excavatable. Further, the only mix with 0 % CKD showing 91 days UCCS (0.89 MPa) above 0.70 MPa shall be machine excavatable and other mixes (UCCS 0.07-0.57 MPa) excavatable manually or by conventional digging apparatus.

In terms of applications, the mixes SR-CKD-00 and SR-CKD-25 having 28-day UCCS between 0.70-2.10 MPa can be used as structural fill like foundation supports, retaining walls etc. and excavatable backfill like utility pipe-lines, storm-drainage pipe-lines, roadway-trench, conduit-bed etc. (Ling et al., 2018b). Other mixes SR-CKD-50, SR-CKD-75 and SR-CKD-100 showing UCCS less than 0.50 MPa were suitable for general backfill like void-fill, abandoned underground structures etc. with early setting is not being critical.

Further, all the mixes with CKD being excavatable manually or with conventional equipment proved sustainable in terms of energy consumption compared to the mix requiring mechanical equipment. Mix with 75 % CKD with reasonable setting time, strength and using maximum by-products was most appropriate in terms of practicality and sustainability.

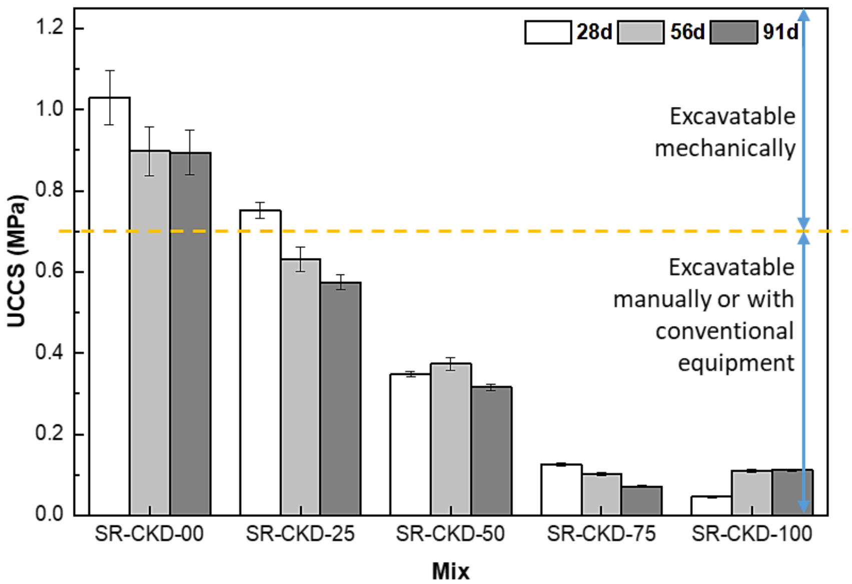


Figure 4.30 Unconfined compressive strength of Group-3 CLSM mixes

Further, Group-1 mixes 28 days compressive strength results were ranged between 0.06-0.59MPa and 91 days results ranged between 0.09-0.95MPa. Comparatively lower values in Group-1 mixes than Group-3 mixes mentioned in Table 4.9 are due to high binder to aggregate ratio of 1;10 (poorer mix) in comparison to richer ratio of 1:3 for Group-3 mixes. Comparing the results with Group-2 mixes that used only RHA as fine aggregate with binder to aggregate ratio of 1:3 same as in Group-3, the 28 days strength ranged between 0.03-.31MPa and 91 days strength ranged between 0.05-0.48 MPa. These are very low values compared to Group-3 mixes. The reason for such low compressive strength is use of highly porous RHA and the resulting requirement of high w/b of 8.25 for required flowability. Notably w/b for Group-3 mixes ranged between 3.71-4.57. Also, use of stronger aggregate SFS has been better than highly porous aggregate RHA.

4.4.7 California bearing ratio (CBR)

The CBR test was performed at the age corresponding to the ball drop setting time to achieve 76 mm indentation diameter on the CLSM surface. The mix with 100 % CKD could not develop enough stiffness to achieve the ball drop indentation diameter of 76 mm and the CBR test was done at 28 days. The results are presented in Table 4.9 and Figure 4.31. The CBR values for the Group-3 CLSM mixes were in the range of 7.7-20.3 %. The results depicted that the progressive addition of CKD as replacement of OPC in the CLSM mixes caused reduction of the CBR value. Reduced strength gain or delayed setting resulting from increased CKD content in the CLSM mixes as discussed in above sections explains the reduction of CBR being a strength parameter.

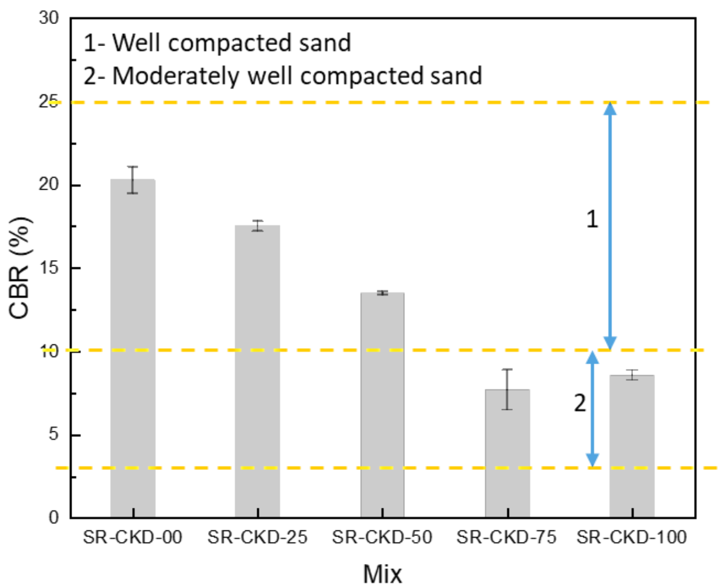


Figure 4.31 California bearing ratio (CBR) of Group-3 CLSM mixes

A subgrade can be categorized as slightly compacted sand when its CBR value is 3 % and a well compacted sand with CBR value within 10 and 25 % (Knapton, 1999). Accordingly, subgrade having CBR value between 3-10 % could be considered as moderately well compacted sand. Therefore, the mixes SR-CKD-00, SR-CKD-25 and SR-CKD-50 with CBR

13.43-20.27% may be designated as well compacted sands and SR-CKD-75 and SR-CKD-100, having CBR 7.7 % and 8.6 % i.e., between 3-10 %, as moderately well compacted sand. Additionally, in respect of application, all the Group-3 CLSM mixes are having CBR values above the typical range of 2-5 % shall be suitable as structural fill material in road embankments (Arulrajah et al., 2017b). It is seen that CBR and UCCS results are in positive correlation as reported earlier (Lachemi et al., 2008; Naganathan et al., 2012). Assessment of the results shows SR-CKD-75 presenting maximum suitability in respect of CBR with due consideration of setting time and sustainability.

CBR results of Group-3 mixes ranging between 7.67-20.27 % are lower compared to CBR of Group-1 mixes ranged between 10.9-34.9 %. Higher CBR values in Group-1 is due to difference of stronger aggregate SFS used in comparison to 50% use of porous and flexible aggregate RHA in Group-3 mixes. It can be seen that the aggregates used in the CLSM have an impacted on the CBR value. Only 0 % CKD mix in Group-2 achieved ball drop resistance for 76mm indentation and its CBR value of 15.84% also was lowest compared to correspondingly 0% CKD mix in Group-1 and Group-3. This is owed to use of only RHA as aggregate in Group-2 compared to use of SFS partially in Group-3 and fully in Group-1 mixes.

4.4.8 Drying shrinkage

The results of drying shrinkage development with the passage of time are presented in Table 4.9 and Figure 4.32. The shrinkage strain in all the mixes increased with the increase in drying duration. Similar to Group-1 CLSM, the shrinkage increased at higher rate during initial drying period of around 25 days and rate slowed down thereafter and attained the ultimate shrinkage level by 81 days. Shrinkage strain at 81 days of drying for CLSM mixes ranged between 0.255-0.026 %. Comparison of the results indicate that ultimate shrinkage decreased as CKD proportion increased in binder in CLSM mix. This trend was similar to Group-2 CLSM but opposite to the general trend of increase in shrinkage with the addition of CKD as replacement of cement seen in Group-1 CLSM as well as other studies (Katz and Kovler, 2004; Lachemi et al., 2008). The previous studies and Group-1 CLSM used crushed sand, natural sand and spent foundry as filler materials. In the Group-3 study, use of RHA known to have a vesicular structure that acted as an internal reservoir and provided a source of water curing even at later age (de Sensale et al., 2008; Wang et al., 2021). Similarly, as in Group-2 CLSM, the internal curing effect of RHA had a dominating influence upon shrinkage in Group-3 also. All the mixes with CKD have lesser ultimate shrinkage than 100 % OPC mix and therefore are more stable. Another prominent feature of drying shrinkage curves is the inflection of curves in the initial drying period of 7 days, which indicates an initial expansion phase. This can be owed to re-absorption of the bleeding water from the specimen surface at initial stage due to the presence of RHA. Similar observation was also made by de Sensale et al. (2008) while using RHA as cement replacement in conventional mortar mixes.

Ultimate shrinkage level was attained in 81 days in Group-1 and Group-3 but in 180 days in Group-2. Group-2 used only RHA as fine aggregate along with high water/binder ratio of 8.25. High water absorption in Group-2 mixes needed longer time for drying. The typical ultimate drying shrinkage of concrete in structures is reported to be 0.06 % (ACI 224R-01, 2001; Vardhan et al., 2019). Except SR-CKD-100, the ultimate shrinkage of all the CLSM mixes in Group-3 study ranging between 0.255-0.1170% is more than concrete. Notably, CLSM are quite different from concrete and use a high water content to achieve high fluidity which is known to result in high shrinkage (Chindaprasirt et al., 2004). Further, ultimate shrinkage strain of the order of 0.25 % for CLSM using CKD has been reported earlier (Lachemi et al., 2008).

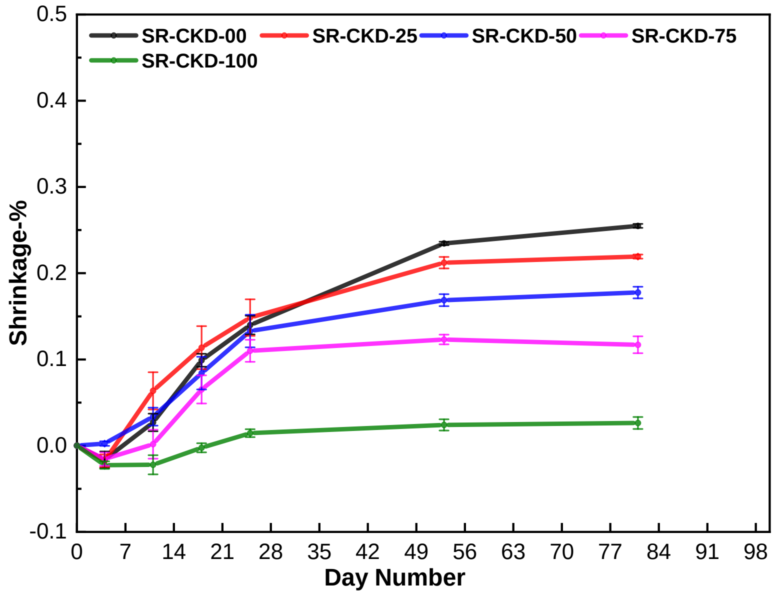


Figure 4.32 Drying shrinkage versus Time of Group-3 CLSM mixes

4.4.9 Permeability

Permeability of the CLSM mixes was tested at 28 days as per IS:3085 (IS:3085, 1965). The specimens were immersed for saturation prior to testing in order to expedite the process as suggested by Lachemi et al. (2008, 2007) and Thaha (2007). Specimen of mix with 100 % CKD crumbled due to inadequate binding attained and thus, its testing was not possible. The coefficient of permeability (K) of the four CLSM mixes ranged between 1.29×10^{-4} to 6.13×10^{-4} cm/sec and the results are presented at Table 4.9 and Figure 4.33.

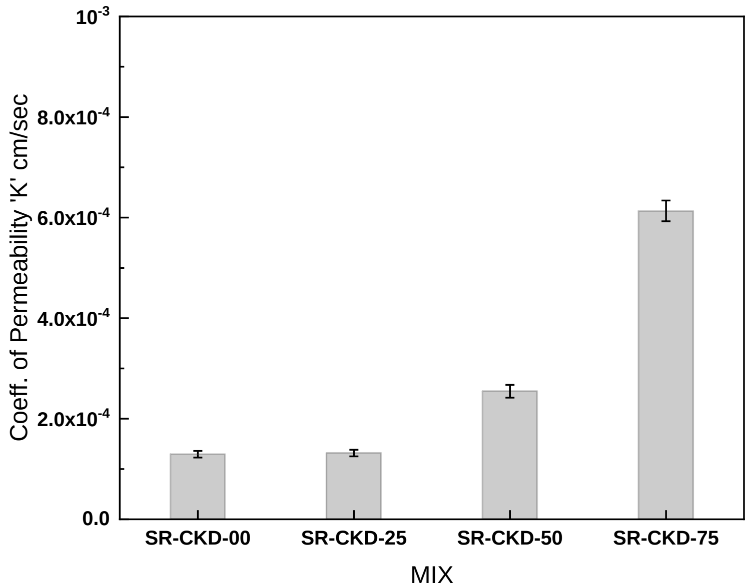


Figure 4.33 Coefficient of Permeability 'K' of Group-3 CLSM mixes

The results indicate an increased permeability due to addition of higher CKD content by replacing cement in CLSM mixes. It is opposite to the trend of reduction in permeability due to the addition of CKD as replacement of cement seen in Group-1 CLSM and the past study by Al-Harthy et al. (2003). The above studies used spent foundry and natural sand as fine aggregate materials along with CKD. However, Group-3 permeability trend was similar to Group-2. In Group-3 mixes, in addition to CKD used as binder, RHA and SFS have been used as fine aggregate. The permeability of the mixes has been prominently influenced by presence of RHA. RHA particles being highly porous by nature are supposed to augment porosity of the mix and potentially affect permeability (Venkatanarayanan and Rangaraju, 2015). Moreover, the addition of CKD resulting into reduced cement content shall also cause a reduced hydration and pozzolanic activity thereby rendering the CLSM mix more porous/permeable. All the tested CLSM mixes in Group-3 have permeability around the above range of 10^{-4} - 10^{-5} cm/sec equivalent to excavatable CLSM, compacted granular fill and clean sand with good draining ability (ACI 229R, 1999; Terzaghi et al., 1996). Permeability is desirable for insulation and isolation fill (Wu et al., 2016).

4.4.10 Mineral phase identification (XRD) and microstructure (FESEM, EDS)

Mineral phase identification through XRD scan followed by analysis with the help of X'pert Highscore Plus is presented at Figure 4.34. Prominent phases of quartz (Q), calcite (C), and hydration products ettringite (E)), portlandite (CH) and clinozoisite (Cl) and gypsum (G) were observed. Phases of hydration products E, CH and Cl indicated a strength activity in the mixes having some cement content as binder. Phases of CH and E in the 100 % CKD mix reflected some cementitious behavior of CKD. However, the same was insignificant keeping in view the crumbling of the specimen when immersed during permeability tests. Gypsum phase observed in a CLSM at 28 days shows an incomplete reaction because of inadequate reactants for hydration activity (Devaraj et al., 2023; Do et al., 2019). Presence of gypsum in XRD scan, reflective of a crystalline phase, is known to cause microcracks, accelerated deterioration and reduction of strength (Vafaei and Allahverdi, 2017; Zhang et al., 2016). The long-term effect of gypsum is generally seen in terms of drying shrinkage strain and the development of drying shrinkage for 81 days in present study did not reflect any effect of gypsum presence, as the very small peaks represented an insignificant gypsum phase in hardened CLSM. The phase composition for the Group-3 CLSM mixes has remained similar qualitatively suggesting the CKD used to be almost inert. Similar results were seen in Group-1 and Group-2 CLSM also.

Imaging by FE-SEM and EDS scanning results for the Group-3 CLSM are presented in Figure 4.35 (a)-(e). Phases such as calcite (C), calcium silicate hydrate (CSH) and ettringite (E) were seen in FE-SEM images of CLSM mixes with 0-75% CKD (i.e., cement 100-25%). Calcium hydroxide (CH) phases were not available probably due to its participation in pozzolanic reaction with RHA resulting into CSH gel phases. Specimen of CLSM mixes with 0 % and 25 % CKD present a denser microstructure with more hydration products such as CSH, C and E along with fewer and small voids. Large sized voids and fewer hydration products seen in images of the CLSM mixes with 50 % and 75 % CKD reflected a less compact/dense microstructure compared to SR-CKD-00 and SR-CKD-25. Compressive strength for the mixes related well to the comparative denseness of microstructure accordingly. Image of 100 % CKD mix showed no hydration products, had large voids and only unreacted particles of mix materials which pointed towards the CKD's inert nature. Very low compressive strength of SR-CKD-100 was a reflection of the above factors. Mechanical property and microstructural character of the CLSM mixes have been correlated earlier also (Ho et al., 2022; Hwang et al., 2017). Crumbling of SR-CKD-100 mix specimen during immersion in water before permeability test, reflected no or inadequate binding in Group-3 also. Any insignificant binding seen in SR-CKD 100 may be owing to small hydration activity and the interlocking effect among mix constituents.

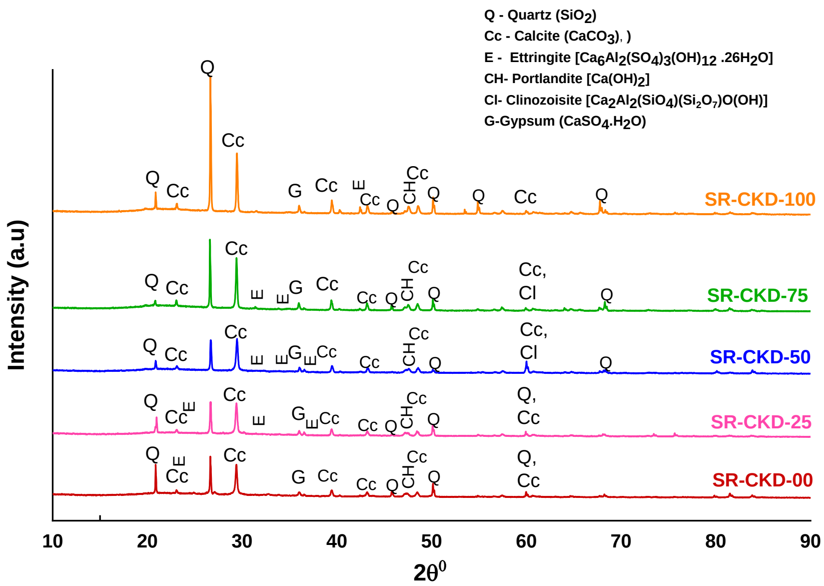
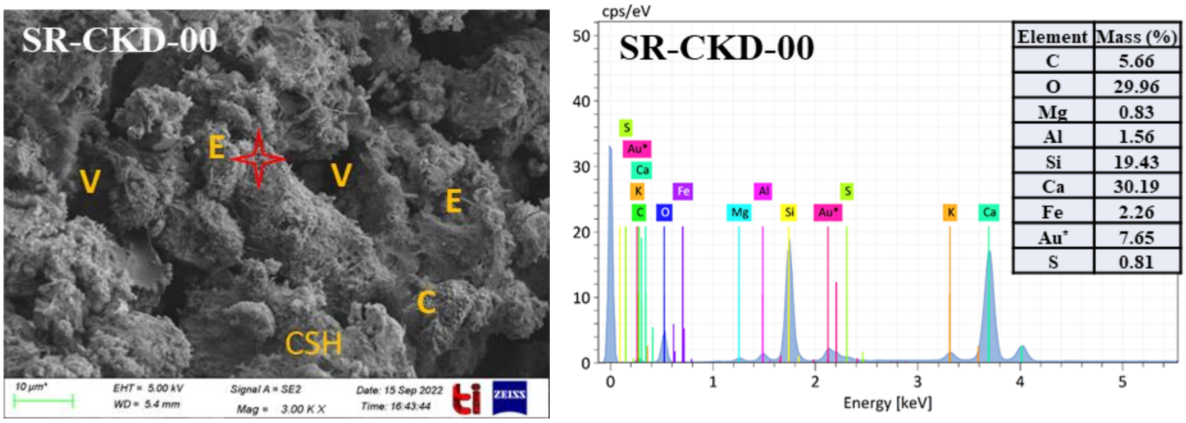
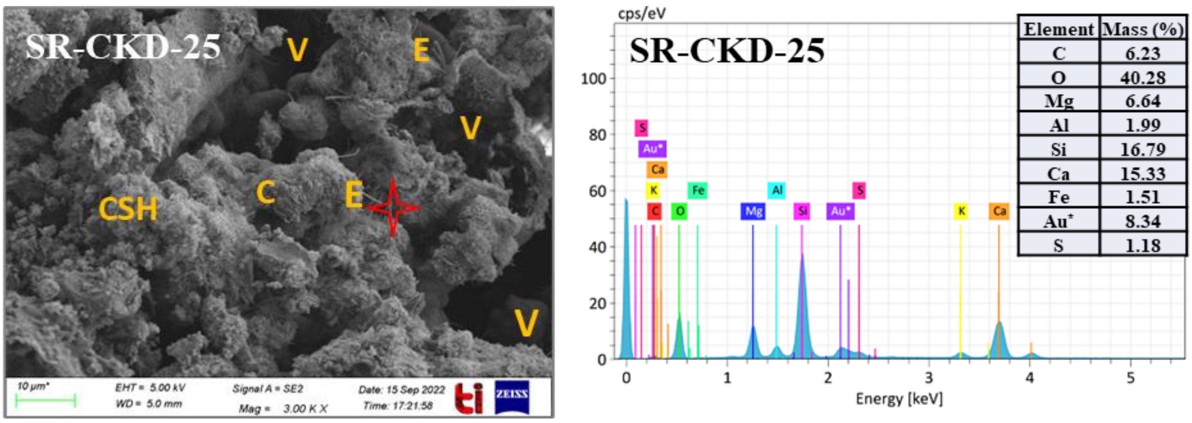


Figure 4.34 XRD scan of Group-3 CLSM mixes



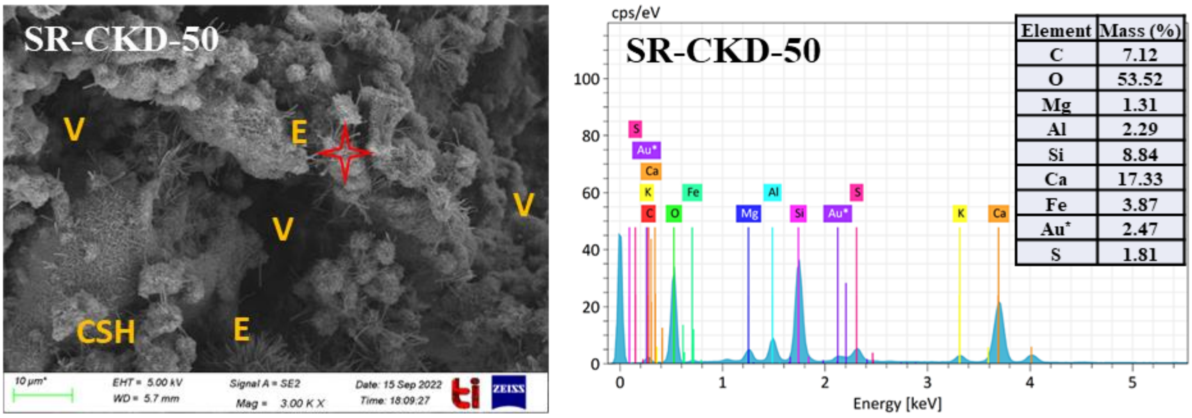
Element	Mass (%)
C	5.66
O	29.96
Mg	0.83
Al	1.56
Si	19.43
Ca	30.19
Fe	2.26
Au*	7.65
S	0.81

(a)

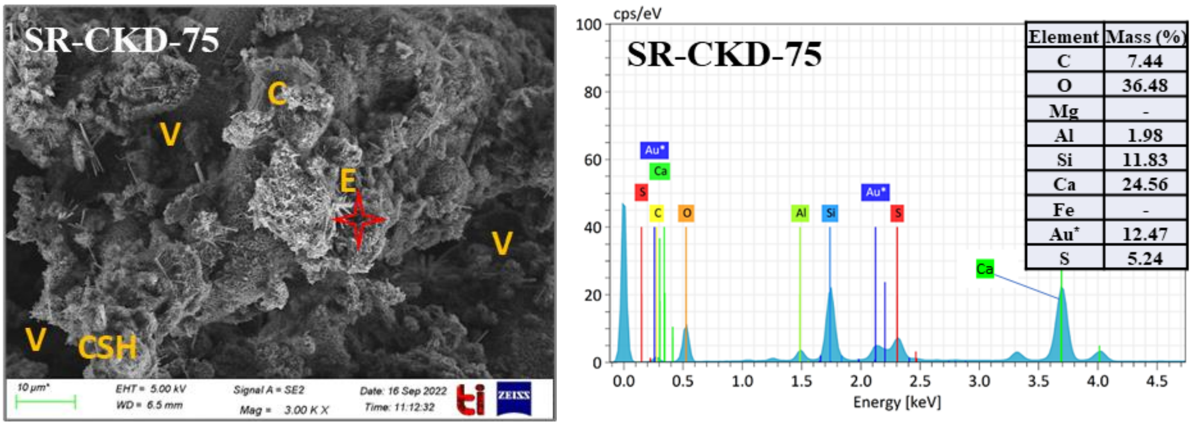


Element	Mass (%)
C	6.23
O	40.28
Mg	6.64
Al	1.99
Si	16.79
Ca	15.33
Fe	1.51
Au*	8.34
S	1.18

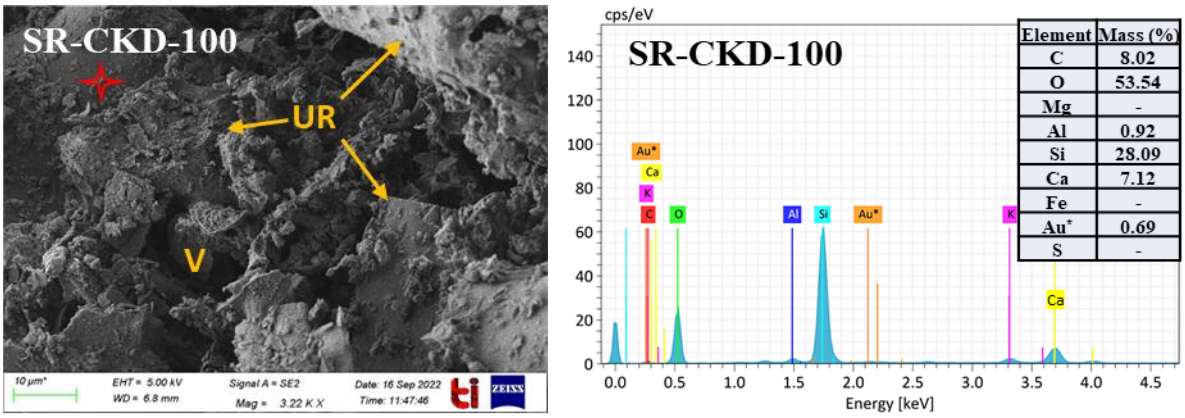
(b)



(c)



(d)



(e)

Figure 4.35 FE-SEM and EDS image of Group-3 CLSM mixes (a) SR-CKD-00; (b) SR-CKD-25 (c) SR-CKD-50 (d) SR-CKD-75 and (e) SR-CKD-100

Proportion of the major reactants in the chemical composition of the mixes, examined through EDS analysis, namely Si, Al and Ca are tabulated at Table 4.10. The Si/Al ratios of 12.34 to 16.08 for the mixes with 0-100 % CKD depicted a general rising trend among majority of Si/Al ratio of mixes corresponding to increased CKD proportion. Decreasing strength with addition of CKD in Group-3 CLSM mixes was validated by trend of rising Si/Al ratio's correlation with lower strength reported in literature (Chindaprasirt et al., 2009; Ho et al., 2022; Hwang et al., 2017).

Table 4.10 EDS analysis of Group-3 CLSM mixes

Mix	Average quantity by mass (%)			Si/Al
	Si	Al	Ca	
SR-CKD-00	13.70	1.11	25.10	12.34
SR-CKD-25	13.70	1.03	18.84	13.30
SR-CKD-50	21.88	1.12	18.33	19.53
SR-CKD-75	23.56	1.33	13.60	17.71
SR-CKD-100	17.37	1.08	14.83	16.08

4.4.11 Leachate Toxicity

Strength of heavy metals namely, Pb, Cd, Cu, Cr, Zn, Ni, Ba, Li, Sr and Mg in the CLSM mixes including respective regulatory limits or parametric values are presented in Table 4.11. The heavy metal concentrations in the leachate of all the mixes in Group-3 CLSM are within regulatory limits and therefore, they were non-hazardous and safe as backfill. The CLSM mixes were obtained by using all proposed by-products SFS, RHA and CKD for the study and the heavy metal concentrations in leachate of the mixes were within the allowable limits.

Table 4.11 Toxic metal concentration as per TCLP of Group-3 CLSM mixes

Mix	Metal concentration (mg/L) in CLSM									
	Pb	Cd	Cu	Cr	Zn	Ni	Ba	Li	Sr	Mg
SR-CKD-00	0.44	<0.01[a]	<0.05[a]	0.35	<0.05[a]	0.05	0.42	0.1	1.51	68.1
SR-CKD-25	0.46	<0.01[a]	<0.05[a]	0.11	<0.05[a]	0.05	0.62	0.07	1.53	69.7
SR-CKD-50	0.44	<0.01[a]	<0.05[a]	<0.05[a]	<0.05[a]	0.05	0.81	0.06	2.09	75.8
SR-CKD-75	0.54	<0.01[a]	<0.05[a]	<0.05[a]	0.68	0.09	0.9	0.06	2.92	74.9
SR-CKD-100	0.59	<0.01[a]	<0.05[a]	<0.05[a]	5.42	0.11	0.7	<0.05[a]	4.17	34.7
Parametric value (mg/L)	5	1	130[b]	5	500[b]	70[b]	100	-	2000[b]	3000[c]

[a] Below Detection Limit
[b] 100 times the levels specified in EPA 822-F-18-001 titled 'Drinking Water Standards and Health Advisories'
[c] 100 times the levels specified in IS:10500 titled 'Indian Standard Drinking Water Specifications'

4.5 COMPARATIVE ANALYSIS OF DIFFERENT GROUPS OF CLSM MIXES

Comparative analysis regarding important practical aspects of the CLSM such as fresh and hardened unit weight, setting time, unconfined compressive strength, California bearing ratio and quantum of by-product utilization in different CLSM groups under study are discussed hereunder.

4.5.1 Fresh state Unit weight

Lesser unit weight backfill puts lower pressure that allows leaner design of utility elements and helps sustainability. Fresh unit weights of all the groups are reported in Table 4.12. It can be seen that mixes with spent foundry sand had the highest unit weight among all groups; while mixes with rice husk ash has the least unit weight. It is due to highly porous structure as well as low specific gravity of rice husk ash particles compared to solid structure of the spent foundry sand. It is to be mentioned that even the mixes with spent foundry sand have unit weight on the lower side of a specified range for normal CLSM (1840-2320 kg/m^3). Among the three groups, mix S-CKD-75 had least unit weight of 1834 kg/m^3 in Group-1, R-CKD-100 with 1225 kg/m^3 lowest in Group-2 and SR-CKD-75 with 1391 kg/m^3 in Group-3. It clearly showed that the replacement of cement by CKD leads to decrease in unit weight, due to low specific gravity of CKD compared to cement.

Table 4.12 Fresh state unit weight of all CLSM mixes in various groups

Group	Series	Fresh Unit Weight
Group-1	S-CKD	1834-1852 kg/m^3,
Group-2	R-CKD	1224-1242 kg/m^3
Group-3	SR-CKD	1391-1446 kg/m^3

4.5.2 Setting time

Setting time is significant for putting the CLSM backfill into service. The setting time results of the three groups of CLSM examined with respect to penetration resistance and ball drop resistance methods are presented in Table 4.13.

It can be seen that all groups of CLSM achieved stiffness of the level of initial setting time at PR=0.344 MPa which is suitable for allowing human foot traffic. Maximum initial setting time was taken by rice husk ash mixes of Group-2 and least by mixes with spent foundry sand plus rice husk ash of Group 3. Final setting time corresponded to PR=2.76MPa considered as the threshold for vehicular load. On comparing the final setting time results of the groups, it is observed that the rice husk ash mixes in Group-2 with only up to 50 % CKD could attain the stiffness level of final setting time. The minimum time was again taken by mixes using spent foundry sand plus rice husk ash of Group-3. Highest setting time and some of the mixes not attaining desired final setting level in Group-2 were due to use of highly porous rice husk ash, high water content (w/b=8.25). Lowest setting time of mixes using spent foundry sand plus rice husk ash in Group-3 are possibly due to comparatively lower w/b around 3.7-4.6. The setting times in case of spent foundry sand mixes of Group-1 is higher than Group-3, which is due to higher binder to aggregate ratio of 1:10 and flow of around 250mm compared to the ratio of 1:3 and flow of 200mm in Group-3 mixes.

It was also observed that between 100% CKD to 75% CKD in the mixes, the setting time improved substantially with addition of even 25% cement. This is possibly owing to pozzolanic activity due to availability of alkalis from cement paste and CKD. Further, with respect to maximum use of a by-product CKD (sustainability) and setting time (PR), Group-1 mix S-CKD-75 mix showing initial and final setting time as 15 and 120 hours, Group-2 mix R-CKD-50 as 29 and 598 hours and Group-3 mix SR-CKD-75 as 8 and 97 hours were best in their respective Group. Therefore, best practical CLSM mixes in Group-1 and 3 suggest using at least 25% cement as binder for optimum performance. Similarly in Group-2 mixes cement at least 50% as binder would be optimum.

Table 4.13 Setting time (PR) and ball drop test of all CLSM mixes in various groups

Group	Series	Setting time as per penetration resistance		Setting time as per Ball drop resistance	
		Initial Setting time (PR=0.344MPa)	Final Setting time (PR=2.76MPa)	(Indentation = 76mm)	(Indentation = 100mm)
Group-1	S-CKD	11-82 hours	38-873 hours	113-848 hours	-
Group-2	R-CKD	12-190 hours	29-598 hours *(Only up to 50% CKD Mix)*	1116 hours *(Only 0% CKD Mix)*	361-1031 hours *(Only 25-50% CKD Mix)*
Group-3	SR-CKD	5-53 hours	42-218 hours	141-648 hours *(Only up to 75% CKD Mix)*	373 hours *(100% CKD Mix)*

Further, it is seen that all spent foundry sand mixes of Group-1 attained the stiffness level of 76mm indentation suitable for utility trench fill. Only one mix using rice husk ash could achieve the stiffness level of 76mm indentation. However, 100 mm indentation level suitable for pavement sub-grade was attained by 25-50 % CKD mixes. Spent foundry sand plus rice husk ash mixes of Group-3 with up to 75% CKD attained 76mm stiffness level. SR-CKD-100 could achieve 100mm indentation level. Among the groups spent foundry sand mixes attaining desired ball drop resistance level was best. Considering overall setting behaviour, clocking minimum setting time (PR) and achieving ball drop 76mm stiffness level in comparable time, Group-3 mix SR-CKD-75 was best among all the groups.

4.5.3 Hardened state Unit weight

Hardened unit weights of the CLSM mixes are presented in Table 4.14. Unit weight of all the mixes in AU state are less or very close to unit weight 1650 kg/m^3 of a compacted earth fill or normal CLSM. Oven dried unit weight is further less due to drying up of moisture. Among the groups the spent foundry sand mixes have the highest AU unit weight which is around that of compacted earth. Lowest AU unit weight is for rice husk ash mixes due to use of highly porous structure of rice husk ash as well as high w/b ratio. Considering imposed weight upon the embedded utility elements the rice husk ash mixes (Group-2) shall be best with lowest weight. Within the groups, mix S-CKD-00 of Group-1 with an AU unit weight as 1546 kg/m^3 and OD unit weight 1403 kg/m^3, mix R-CKD-50 of Group-2 with an AU unit weight as 1053 kg/m^3 and OD unit weight 417 kg/m^3 and Group-3 mix SR-CKD-75 with an AU unit weight as 1005 kg/m^3 and OD unit weight as 661 kg/m^3 have lowest unit weight in their respective group. Further the mix R-CKD-50 with minimum unit weight shall be best among all mixes with respect to this aspect. Low density CLSM are suitable for application as insulation and isolation fill and also for weak soil conditions. The strength parameters such as compressive strength, CBR for the CLSM mixes also needed to be suitable while considering suitability with respect to unit weight.

Table 4.14 Hardened state unit weight of all CLSM mixes in various groups

Group	Series	Unit weight as-unmoulded (AU)	Unit weight oven dried (OD)
Group-1	S-CKD	1546-1855 kg/m^3	1403-1584 kg/m^3
Group-2	R-CKD	1053-1178 kg/m^3	416-585 kg/m^3
Group-3	SR-CKD	1005-1243 kg/m^3	661-737 kg/m^3

4.5.4 Unconfined compressive strength (UCCS)

The UCCS of all the mixes at 28 days and 91 days is reported in Table 4.15. In terms of 28 days strength, spent foundry sand plus rice husk ash mixes (Group-3) have the highest strength development and only rice husk ash mixes had lowest strength. Lower strength of rice husk ash mixes (Group-2) was attributed to use of highly porous rice husk ash in comparison to denser spent foundry sand particles in other groups. In addition, a high w/b ratio (8.25) of rice husk ash Group-2 mixes also have caused lower strength. Further, low w/b (around 4.5) and richer binder aggregate ratio (1:3) and addition of denser spent foundry sand as 50% replacement of rice husk ash as fine aggregate in Group-3 provided highest strength. Spent foundry sand mixes of Group-1 for poorer binder aggregate ratio 1:10 have showed comparatively lower strength than Group-3 mixes.

Table 4.15 Unconfined compressive strength of all CLSM mixes in various groups

Group	Series	UCCS (28 days) MPa	Application	UCCS (91days) MPa	Excavatability
Group-1	S-CKD	0.06-0.59	• S-CKD-00 > 0.50 MPa, suitable for utility backfill • Other mixes < 0.50MPa, suit general backfill	0.09-0.95	• Mix with 0% CKD. 0.70MPa, excavatable mechanically • Other mixes < 0.70MPa, excavatable manually or with conventional equipment
Group-2	R-CKD	0.03-0.31	• With setting time consideration, mixes with 0-50% suitable for general backfill	0.05-0.48	All mixes < 0.70MPa, excavatable manually or with conventional equipment
Group-3	SR-CKD	0.05-1.03	• Mixes with 0-25% CKD > 0.70 MPa, suitable for structural fill • Other mixes < 0.50 MPa, suitable for general backfill	0.07-0.89	• Mix with 0% CKD. 0.70MPa, excavatable mechanically • Other mixes <0.70 MPa, excavatable manually or with conventional equipment

The application of the CLSM is considered with respect to 28 days UCCS. Spent foundry sand mix of Group-1, S-CKD-00 strength 0.594 MPa greater than 0.50 MPa suited excavatable utility backfill purpose and other mixes suitable for general backfill applications. Keeping in view the achievement of final setting level, rice husk ash mixes of Group-2 with CKD 0-50 % were suitable for general backfill applications purposes. Spent foundry sand plus rice husk ash mixes of Group-3 SR-CKD-00 and SR-CKD-25 with UCCS (0.75-1.03 MPa) between 0.70-2.10 MPa are suitable for structural fill such as foundation supports, retaining walls etc. Other Group-3 mixes were suitable for general backfill such as void-fill, abandoned underground structures etc. where early setting is not critical. Spent foundry sand mixes Group-1 and mixes with spent foundry sand plus rice husk ash Group-3 were best suited with respect to higher bearing strength application.

Excavatability is governed by long term (91 days) UCCS. Group-1 mix S-CKD-00 having 91 days strength 0.946 MPa greater than 0.70 MPa was mechanically excavatable and other mixes were excavatable manually or with conventional equipment. In Group-2, all mixes having strength less than 0.70 MPa were manually excavatable. Like Group-1, mix SR-CKD-00 in Group-3 had strength 0.89 MPa greater than 0.70 MPa, was machine excavatable and other mixes (0.07-0.57 MPa) less than 0.70 MPa excavatable manually or with conventional equipment. In terms of excavatability, Group-2 mixes were most suited with respect to lower energy requirements.

Among the groups, with respect to maximum by-product utilization with reasonable strength along with practical aspect of setting time, S-CKD-75, R-CKD-50 and SR-CKD-75 were best.

4.5.6 California bearing ratio-CBR

California bearing ratio results of the CLSM mixes at ball drop resistance time (76mm indentation) are shown in Table 4.16. It can be seen that among the groups, mixes with spent foundry sand (Group-1) achieved highest range of CBR values. The rice husk ash mixes (Group-2) except 0% CKD mix couldn’t achieve ball drop resistance for 76 mm indentation. The mixes using spent foundry sand along with rice husk ash (Group-3) however had CBR values range less than Group-1. Use of solid spent foundry sand as aggregate in Group-1 mixes compared to porous rice husk ash in other groups resulted in higher CBR.

Spent foundry sand mixes S-CKD-00, S-CKD-25 and S-CKD-50 had CBR between 25-50 % can support pressure equivalent to very well compacted sand. Mixes S-CKD-75 and S-CKD-100 with CBR between 10-25% were equivalent to well compacted sand. Only Group-2 mix R-CKD-00 with CBR 15.84% can be considered equivalent to well compacted sand. Group-3 mixes SR-CKD-00, SR-CKD-25 and SR-CKD-50 having CBR between 10-25% can support bearing pressure equivalent to a well compacted sand. Mixes SR-CKD-75 and SR-CKD-100 with CBR between 3-10 % shall support bearing pressure as a moderately well compacted sand. All the CLSM mixes tested for CBR attained strength equivalent to moderately to very well compacted sands. However, S-CKD-75 in Group-1, R-CKD-00 in Group-2 and SR-CKD-75 with CBR (3-25%) appropriate for moderately to well compacted sand were best suited for backfill applications keeping in view the other practical aspects such as setting time, strength and sustainability.

Table 4.16 California bearing ratio (CBR) of all CLSM mixes in various groups

Group	Series	CBR (%)	Remarks
Group-1	S-CKD	10.9-34.9	-
Group-2	R-CKD	15.8	*CBR test was conducted at time for ball drop indentation of 76mm. Only 0% CKD mix attained stiffness for 76mm ball drop indentation and its CBR was examined.*
Group-3	SR-CKD	7.7-20.3	-

4.5.7 Sustainability-By-product utilization

Mixes allowing utilization of maximum by-products will be sustainable. The quantities of by-products, water and maximum cement content use for the CLSM mixes are presented in Table 4.17. The spent foundry sand mixes (Group-1) use highest by-products and rice husk ash mixes (Group-2) use the lowest. Spent foundry sand mixes (Group-1) also used lowest water content followed by mixes using spent foundry sand and rice husk ash (Group-3) and rice husk ash mixes (Group-2). With respect to sustainability in terms of quantum of by-product utilization and water content, the Group-1 mixes were best followed by Group-3 and Group-2. Group-1 CLSM mixes used highest quantity of by-product due to binder aggregate ratio 1:10 and lowest water content for required flowability due to very less absorption of SFS used as aggregate. In Group-2 and Group-3, binder to aggregate ration of 1:3 resulted in lesser by product consumption. Also, due to use of highly porous RHA as fine aggregate caused higher water consumption. Within the groups S-CKD-75 with 1344 kg/m^3 by-products, R-CKD-50 with 352 kg/m^3 by-products and SR-CKD-75 with 608 kg/m^3 by-products were best.

Table 4.17 By-product, water and cement utilization of all CLSM mixes in various groups

Group	Series	By-product utilization	Water	Maximum cement content
Group-1	S-CKD	1255-1399 kg/m^3	471-452 kg/m^3	126 kg/m^3
Group-2	R-CKD	304-400 kg/m^3	836-825 kg/m^3	101 kg/m^3
Group-3	SR-CKD	505-750 kg/m^3	739-696 kg/m^3	168 kg/m^3

The above analysis about important practical aspects such as unit weight (fresh and hardened), setting time, unconfined compressive strength, CBR, and by-product utilization and water consumption for the CLSM mixes indicates that Group-1 CLSM mixes using spent foundry sand has shown early setting, good strength, and best scope for maximum utilization of by-products. Group-3 mixes using combination of spent foundry sand and rice husk ash were also comparable but accommodated lesser by-product utilization. Group-2 mixes using rice husk ash showed long setting times, minimum strength and offered minimum consumption of by-products amongst all groups. Group-2 mixes with 75-100 % CKD could not even achieve stiffness equivalent to final setting level (PR) and ball drop indentation of 100 mm. Mix S-CKD-75, R-CKD-50 and SR-CKD-75 were best in their respective group. Further, Group-1 mixes using SFS as aggregate proved better in terms of sustainability, practicality than other Group-2 and Group-3 mixes owing to use of highly porous RHA as aggregate.

4.6 ECOLOGICAL ANALYSIS (GROUP-1, GROUP-2 AND GROUP-3)

Ecological sustainability of the building materials is under continued emphasis due to rising prominence of climate change awareness (McGrath et al., 2012). Use of recycled aggregates, by-product substitutes of cement and alternatives for fuels etc. have been focused upon to reduce ecological foot print by large volumes of construction materials being used in the world. In this respect the energy footprint of a project can be assessed by the embodied energy (EE) of the building materials according to their consumption in the construction (Bansal et al., 2014). The total primary energy consumed for direct and indirect operations like materials extraction and transportation, processing etc. in the limits of cradle-to-gate, to prepare the product ready to leave the final factory gate is termed as embodied energy (EE) and the sum of the carbon dioxide emissions related to fuel and processing is termed as embodied carbon dioxide (ECO_2) (Hammond and Jones, 2011).

The EE and ECO_2 for the mixes have been worked out by multiplying quantity of the constituent in a unit volume of the CLSM with its respective EE and ECO_2 coefficients reported in inventory of carbon emissions (ICE) by Hammond and Jones (2011) and by Gupta et al. (2019). Similar approach of using EE/ECO_2 coefficients from a database has also been used in many previous studies of CLSM and concrete (Chompoorat et al., 2021; M. Kumar et al., 2022; Mithun and Narasimhan, 2016). SFS, RHA and CKD are wastes or by-products which are not produced intentionally by the industry and therefore EE and ECO_2 value for these is presumed as zero in the analysis. Earlier also EE/ECO_2 has been considered as zero for different industrial by-products such as stone processing dust, spent foundry sand, copper slag, high calcium fly ash and steel slag as suggested in literature (Arulrajah et al., 2017a; Chompoorat et al., 2021; Gupta et al., 2019; Sharma and Khan, 2017). Equation (i) and (ii) based upon literature (Devi et al., 2024; Nizam et al., 2018) were used for working out the EE and ECO_2 for different CLSM and other materials like compacted fill etc.

$$EE_{mix} = \sum_{i-j} q_m \times ee_m \quad \text{.........} \text{ (i)}$$

$$ECO_{2\,mix} = \sum_{i-j} q_m \times ec_m \quad \text{.........} \text{ (ii)}$$

where q_m is the quantity of constituent materials (*i to j*) per unit volume of the CLSM/material.

ee_m and ec_m are the coefficient of the EE and ECO_2 of material as per ICE/literature (Gupta et al., 2019; Hammond and Jones, 2011).

Ecological analysis in terms of EE and ECO_2 of Group-1, Group-2 and Group-3 CLSM mixes is presented Table 4.18 & Table 4.19. Further the EE and ECO_2 of the compacted fill, conventional CLSM and lean concrete were also worked out for comparison which are tabulated in Table 4.20. A compacted backfill of natural soil with a density of 1600 kg/m^3 was considered. For the conventional CLSM the mean quantities of constituents specified as per ACI 229R (1999) were taken as cement-75 kg/m^3, natural sand as fine aggregate-1650 kg/m^3 and water-270 kg/m^3. Lean concrete with very low cement content of 120 kg/m^3 specified as per ICE was considered. Coefficient for EE and ECO_2 for additional materials like compacted soil, natural sand, concrete were also taken from ICE/literature (Gupta et al., 2019; Hammond and Jones, 2011).

Group-1 CLSM mixes have EE values reduced ranging between 609.5-4.5 MJ/m^3, Group-2 CLSM mixes between 495.1-8.3 MJ/m^3 and Group-3 ranging between 815.0-7.0 MJ/m^3. Comparison of the EE results of different CLSM mixes of the three Groups showed that EE gradually diminished with increasing addition of CKD in replacement of OPC and is minimum for mix with 100% CKD. Further, Group-1 CLSM mixes have ECO_2 values ranging between 117.7-0.5 $kgCO_2/m^3$, Group-2 CLSM mixes between 95.1-0.8 $kgCO_2/m^3$ and Group-3 ranging between 157.2-0.7 $kgCO_2/m^3$. The ECO_2 value of different CLSM mixes in each group also diminished with addition of CKD as replacement of cement with minimum for mixes with 100% CKD. Primary reason for reduction of EE and ECO_2 has been the use of CKD in place of cement as cement has higher EE/ ECO_2 than zero considered for the by-product CKD, along with reduced water requirement for the mixes having CKD content caused reduction of EE/ ECO_2 in Group-1 CLSM mixes. It is also noted that some mixes have lower EE and ECO_2 due to maximum utilization of by-products but their mechanical performances are lesser also so a balance needs to be found.

Table 4.18 Embodied Energy (EE) analysis of Group-1, 2 and 3 CLSM

CLSM Group	Material	EE (MJ/ kg)	Material quantity per m^3	EE	Material quantity per m^3	EE	Material quantity per m^3	EE	Material quantity per m^3	EE	Material quantity per m^3	EE
Group-1 CLSM			**S-CKD-00**		**S-CKD-25**		**S-CKD-50**		**S-CKD-75**		**S-CKD-100**	
	OPC	4.8	126	604.8	94	451.2	63	302.4	31	148.8	0.00	0.0
	CKD	0	0.00	0.0	31	0.0	63	0.0	94	0.0	127	0.0
	SFS	0	1255	0.0	1250	0.0	1263	0.0	1250	0.0	1272	0.0
	Water	0.01	471	4.7	470	4.7	463	4.6	459	4.6	452	4.5
	Total (EE)			**609.5**		**455.9**		**307.0**		**153.4**		**4.5**
Group-2 CLSM			**R-CKD-00**		**R-CKD-25**		**R-CKD-50**		**R-CKD-75**		**R-CKD-100**	
	OPC	4.8	101.4	486.7	75.9	364.3	50.3	241.4	25.1	120.5	0.0	0.0
	CKD	0	0.0	0.0	25.3	0.0	50.3	0.0	75.3	0.0	100.0	0.0
	RHA	0	304.0	0.0	304.0	0.0	302.0	0.0	301.0	0.0	300.0	0.0
	Water	0.01	836.4	8.4	835.1	8.4	830.2	8.3	828.4	8.3	824.8	8.3
	Total (EE)			**495.1**		**372.7**		**249.7**		**128.8**		**8.3**
Group-3 CLSM			**SR-CKD-00**		**SR-CKD-25**		**SR-CKD-50**		**SR-CKD-75**		**SR-CKD-100**	
	OPC	4.8	168.3	807.7	124.2	596.1	82.2	394.6	40.6	194.7	0.0	0.0
	CKD	0	0.00	0.0	41.4	0.0	82.2	0.0	121.7	0.0	187.5	0.0
	SFS	0	252.4	0.0	248.4	0.0	246.6	0.0	243.4	0.0	281.2	0.0
	RHA	0	252.4	0.0	248.4	0.0	246.6	0.0	243.4	0.0	281.2	0.0
	Water	0.01	739.1	7.4	739.2	7.4	739.8	7.4	741.7	7.4	696.4	7.0
	Total (EE)			**815.1**		**603.5**		**402.0**		**202.1**		**7.0**

EE values for a concrete, compacted fill and conventional CLSM are 1151.5, 720.0 and 499.7 MJ/m^3 respectively. In Group-1 mix with 0 % CKD (S-CKD-00) has EE less than concrete and compacted fill and the mixes with 25-100 % CKD have lesser EE than for concrete, compacted fill as well as conventional CLSM. All Group-2 mixes with 0-100 % CKD have lesser EE than concrete, compacted fill as well as conventional CLSM. In Group-3 mixes, mix with 0 % CKD have EE lesser than concrete only and mix with 25 % CKD have EE lesser than concrete and compacted fill and the mixes with 50-100 % CKD have lesser EE than concrete, compacted fill as well as conventional CLSM. In each group, mixes with 50-100 % CKD having lesser EE are eco-friendlier than concrete, conventional CLSM and compacted fill. Therefore, from ecological aspect, higher CKD content (50-100%) as binder is beneficial and Group-1 and Group-3 mixes with 75% CKD and Group-2 mix with 50% CKD considered best with respect to practicality are in line with ecological considerations also.

ECO_2 values of concrete, conventional CLSM and compacted fill are 141, 78.0, 36.8 $kgCO_2/m^3$ respectively. Group-1 mixes with 0-25 % CKD has ECO_2 lesser than concrete only, mix with 50 % CKD has lesser ECO_2 than concrete and conventional CLSM and mixes with 75-100 % CKD have lesser ECO_2 than concrete, conventional CLSM as well as compacted fill. In Group-2 mixes with 0 % CKD has ECO_2 lesser than concrete only, with 25-50 % CKD lesser than concrete and conventional CLSM and with 75-100 % CKD lesser than concrete, conventional CLSM as well as compacted fill. In Group-3 mixes with 0 % CKD has highest ECO_2 which is more than concrete/conventional CLSM/compacted fill. However, mixes with 25 % CKD have lesser ECO_2 than concrete only, mixes with 50 % CKD have lesser than concrete and conventional CLSM and mixes with 75 % CKD lesser than concrete and conventional CLSM but comparable with compacted fill and mixes with 100 % CKD lesser than concrete, conventional CLSM as well as compacted fill. In each group mixes with CKD-75-100 % are eco-friendlier than concrete, conventional CLSM and compacted fill. Again, from this aspect, higher CKD content (75-100%) as binder is beneficial and the Group-1 and Group-3 mixes with 75% CKD, considered best with respect to practicality, are on the same page.

Many CLSMs mixes using by-products CKD, SFS and RHA have lower EE and ECO_2 compared to concrete, compacted fill and conventional CLSM. However, it is to be noted that the few mixes having higher EE/ ECO_2 would still be sustainable for using by-product SFS or RHA in comparison to conventional CLSM/compacted fill/concrete that used natural aggregates/soil. With major contribution from OPC, addition of CKD reduces cement and correspondingly EE/ECO_2 gets reduced gradually. Keeping in view the reduced ecological impact in terms of EE and ECO_2, utilization of larger content of industrial by-products for the preparation of CLSM is recommendable to augment sustainability.

Table 4.19 Embodied carbon (ECO2) analysis of Group-1, 2 and 3 CLSM

CLSM Group	Material	ECO_2 (kg CO_2/kg)	Material quantity per m^3	ECO_2	Material quantity per m^3	ECO_2	Material quantity per m^3	ECO_2	Material quantity per m^3	ECO_2	Material quantity per m^3	ECO_2
Group-1 CLSM			**S-CKD-00**		**S-CKD-25**		**S-CKD-50**		**S-CKD-75**		**S-CKD-100**	
	OPC	0.93	126	117.2	94	87.4	63	58.6	31	28.8	0.00	0.0
	CKD	0	0.0	0.0	31	0.0	63	0.0	94	0.0	127	0.0
	SFS	0	1255	0.0	1250	0.0	1263	0.0	1250	0.0	1272	0.0
	Water	0.001	471	0.5	470	0.5	463	0.5	459	0.5	452	0.5
	Total (ECO_2)			**117.7**		**87.9**		**59.1**		**29.3**		**0.5**
Group-2 CLSM			**R-CKD-00**		**R-CKD-25**		**R-CKD-50**		**R-CKD-75**		**R-CKD-100**	
	OPC	0.93	101.4	94.3	75.9	70.6	50.3	46.8	25.1	23.3	0.0	0.0
	CKD	0	0.0	0.0	25.3	0.0	50.3	0.0	75.3	0.0	100.0	0.0
	RHA	0	304.0	0.0	304.0	0.0	302.0	0.0	301.0	0.0	300.0	0.0
	Water	0.001	836.4	0.8	835.1	0.8	830.2	0.8	828.4	0.8	824.8	0.8
	Total (ECO_2)			**95.1**		**71.4**		**47.6**		**24.1**		**0.8**
Group-3 CLSM			**SR-CKD-00**		**SR-CKD-25**		**SR-CKD-50**		**SR-CKD-75**		**SR-CKD-100**	
	OPC	0.93	168.3	156.5	124.2	115.5	82.2	76.5	40.6	37.7	0.0	0.0
	CKD	0	0.00	0.0	41.4	0.0	82.2	0.0	121.7	0.0	187.5	0.0
	SFS	0	252.4	0.0	248.4	0.0	246.6	0.0	243.4	0.0	281.2	0.0
	RHA	0	252.4	0.0	248.4	0.0	246.6	0.0	243.4	0.0	281.2	0.0
	Water	0.001	739.1	0.7	739.2	0.7	739.8	0.7	741.7	0.7	696.4	0.7
	Total (ECO_2)			**157.2**		**116.2**		**77.2**		**38.4**		**0.7**

Table 4.20 EE and Embodied carbon analysis of conventional CLSM, compacted fill and concrete

	Embodied energy (EE)							Embodied carbon (ECO_2)			
	EE factor	Conventional CLSM		Compacted fill		Concrete		ECO_2 factor	Conventional CLSM	Compacted fill	Concrete
Material	EE (MJ/kg)	Material quantity per m^3	EE	Material quantity per m^3	EE	Material quantity per m^3	EE	ECO_2 (kg CO_2/kg)	ECO_2	ECO_2	ECO_2
OPC	4.8	75	360.0	-	x	-	x	0.93	69.8	x	-
Sand	0.083	1650	137.0	-	x	-	x	0.0048	7.9	x	-
Water	0.01	270	2.7	-	x	-	x	0.001	0.3	x	-
Rammed Soil	0.45	-	-	1600	720	-	-	0.023	-	36.8	-
Concrete	0.49	-	-			2350	1151.5	0.060	-	-	141
Total			**499.7**		**720**		**1151.5**		**78.0**	**36.8**	**141**

Ecological impact, sustainability and practicality in respect of achievement of reasonable setting time suggests that the CLSM mixes with 75 % CKD using a small proportion of cement to be best suited. It is also notable that utilizing industrial by-products in every scenario will help the sustainability positively. Replacement of natural fine aggregate with industrial by-products like stone processing dust (Gupta et al., 2019), copper slag (Sharma and Khan, 2017) and fine bone china aggregate (Siddique et al., 2019) similarly benefitting in terms of lowering EE, ECO_2 has been underscored in literature also. It is also notable that full benefit from the industrial by-products with respect to EE and ECO_2 shall be availed of, when the field application of such CLSM is adopted in locations near to by-product's source so as to minimize consumption of energy in transportation too.

Chapter 5

CONCLUSIONS

5.1 GENERAL

The main objective of the research study was to evaluate the utilization potential of industrial by-products materials for developing controlled low strength materials (CLSM). The study envisaged investigating the engineering properties of various CLSM mixes in fresh and hardened state using these wastes either as cement or fine aggregate replacement. In addition, leachability characteristics of CLSM mixes were also examined for ascertaining safety aspect of using such materials for various applications. The three groupings of the by-products namely cement kiln dust (CKD), spent foundry sand (SFS) and bio-mass based rice husk ash (RHA) were formulated for development of CLSM mixes for conducting the study. Group-1 CLSM mixes were constituted by using CKD as binder in progressive replacement of cement up to 100 % level and SFS as fine aggregate. Group-2 used unprocessed RHA as fine aggregate while Group-3 used SFS and RHA in 50/50 ratio as fine aggregate. Fresh state tests such as flowability, unit weight, bleeding, setting time as per penetration resistance as well as ball drop resistance were conducted. Hardened state tests such as unit weight, water absorption, unconfined compressive strength, California bearing ratio (CBR), drying shrinkage and permeability were conducted. Microstructure analysis (FESEM, EDS) and phase identification (XRD) of the mixes was also examined. Toxicity of the CLSM Group covering all the by-products was done for ascertaining environmental safety in use of the chosen by-products. Additionally ecological analysis in terms of embodied energy and embodied carbon for the proposed CLSM mixes was also done.

It was found that ecofriendly, environmentally safe, excavatable CLSM mixes with desirable engineering properties can be prepared by using industrial and biobased by-products namely SFS, CKD and unprocessed RHA. Mixes with 75 % CKD in Group-1 and Group-3 were most suited with respect to the practical considerations like setting time, good strength, sustainability in terms of maximum utilization of by-products, environmentally safe in terms of heavy metal leachate toxicity as well as ecological considerations. However, mix with 50 % CKD in Group-2 was most suitable in terms of above-mentioned aspects.

CLSM made by using these by-products can prove to be an innovative sustainable construction material facilitating valorization of agro-based and industrial by-products along with providing an effective infrastructural solution for their large-scale disposal.

5.2 CONCLUSIONS REGARDING CLSM PROPERTIES

Based upon the testing results, their further analysis and discussion, following conclusions can be drawn.

5.2.1 Flowability

Addition of CKD as replacement of cement resulted in reduced water demand of the mix for the desired flow or enhanced the flowability in mixes. Addition of fine CKD led to increased average grain fineness of the matrix and increased packing by filling the voids. Also, lubrication effect was provided by CKD which reduced the interference between coarser particles of the matrix. All these factors helped in better flowability of the mixes. Additionally, in mixes using RHA, progressive replacement of cement with CKD increased flowability of the mixes. It is known that fine RHA particles get absorbed on cement particles due to surface electric charge which leads to trapping of water. With the reduction in cement, RHA absorption and the associated water trapping decreased, which led to availability of more water in the mix and resulted in increased flowability. Above factors had more influence than normal effect of rise in water demand owed to higher surface area of finer particles. However, in Group-3 surface area effect of fine CKD was more effective up to 75% CKD level reflected by marginally higher water demand.

5.2.2 Bleeding

CKD addition as replacement of cement resulted into higher bleeding. Finer CKD particles helped in filling the voids which led to better packing of constituents, thereby resulting in release of more water in the system. Additionally, use of inert natured CKD with very less/no affinity to water resulted in lesser water demand and reduction of cement resulted in less hydration action thereby increasing unreacted water in the system. Above factors enhancing the bleeding had dominant influence compared to general higher surface area effect of finer CKD particles raising the water demand.

5.2.3 Setting time

The setting time for achieving desired penetration resistance and ball drop resistance increased with the addition of CKD as replacement of cement. Reduced cement due to progressive replacement by CKD resulted in diminished hydration/pozzolanic reaction and delayed stiffening of mix. The inert nature, high LOI and SO_3 of CKD also resulted in delayed setting of the mixes. Group-1 mixes attained the stiffness level of final setting time as per penetration resistance as well as for 76 mm indentation as per ball drop test. Group-2 using RHA as fine aggregate showed quite long setting times owed to very high w/b ratio for achieving desired flowability. In this group, mixes with CKD above 50 % replacement level could not achieve final setting time level (PR=2.76 MPa). With respect to ball drop resistance test, no mix (except the base mix of 0% CKD) could achieve stiffness level for 76 mm indentation, indicating that only 0% CKD mix was suitable for utility trench backfill. However, in this group, mixes up to 50% CKD achieved stiffness level for 100mm indentation, reflecting these mixes' suitability for pavement subgrade application. All Group-3 mixes attained the final setting level as per penetration resistance. Except mix with 100% CKD, all mixes in Group-3 achieved 76mm indentation level that made them suitable for utility trench backfill. However, Group-3 mix with 100 % CKD was able to attain 100mm indentation indicating its suitability as pavement subgrade application.

The setting behaviour confirms that Group-1 mixes using spent foundry sand and Group-3 using both spent foundry sand and rice husk ash as fine aggregates, attained sufficient stiffness for their practical applicability. However, in Group-2 using only rice husk ash as fine aggregate, mixes with only up to 50% CKD presented some practical suitability. Considering achievement of sufficient setting level (in terms of penetration resistance (PR=2.76MPa) suitable for vehicular load and ball drop indentation=76mm suitable for utility trench) for practical application and maximum utilization of waste by-products, the mixes S-CKD-75 and SR-CKD-75 were considered best in their respective groups.

5.2.4 Unit weight

Addition of CKD as replacement of cement resulted in reduction of fresh unit weight of the CLSM mixes. This was attributed to lower specific gravity (2.57) of CKD which replaced the cement having higher specific gravity (3.10). Mixes using RHA as fine aggregate also showed fresh unit weight quite lower than a normal CLSM. This was attributed to use of very low specific gravity of RHA (1.51) compared to natural sand (around 2.60) in a normal CLSM.

Considering hardened unit weight, Group-1 and Group-2 CLSM mixes' higher as-unmoulded unit weight was observed for addition of CKD, which can be attributed to higher bleeding that resulted in more settlement/packing of the mix. In Group-3 mixes with up to 75 % CKD a reduced bleeding rendered less dense mixes and showed decreased as-unmoulded unit weight. Loss of moisture by drying resulted into lower oven dried unit weight than as-unmoulded unit weight.

5.2.5 Unconfined compressive strength (UCCS)

In all the CLSM mixes, UCCS decreased with increased addition of CKD as replacement of OPC. Addition of CKD as cement replacement led to reduction of strength reactants like alite and belite etc. that caused reduction of strength. Also, CKD with high loss on ignition of CKD interferes with the hydration process that also impacted the strength adversely.

UCCS also increased with age in almost all the mixes, except some of the mixes in Group-3. The reduced long-term UCCS in some of Group-3 mixes could be attributed to curing in the air resulting into non-availability of sufficient internal moisture for hydration as well as evolution of cracking by drying shrinkage.

The mixes SR-CKD-00 and SR-CKD-25 having 28-day UCCS between 0.70-2.10 MPa can be used as structural fill like foundation supports, retaining walls etc. All other mixes are suitable for general backfill applications like void filling and abandoned underground structures. Also, all the CLSM mixes are excavatable and most are either excavatable manually or with conventional equipment.

5.2.6 California bearing ratio (CBR)

CBR is a reflection of allowable bearing pressure of the subgrade. The CBR test was performed at the age corresponding to the ball drop setting time for 76 mm indentation on the CLSM surface. Progressive addition of CKD as replacement of OPC in the CLSM mixes caused reduction of the CBR value. Reduced strength or delayed setting resulting from increased CKD content caused reduction of CBR value. CBR and UCCS results are positively correlated. All tested CLSM mixes were equivalent to subgrade between moderately to very well compacted sand.

5.2.7 Drying shrinkage

The shrinkage increased at higher rate during initial drying period of around 25 days and rate slowed down thereafter till attainment of ultimate shrinkage level. In the Group-1 CLSM using spent foundry sand as fine aggregate, the ultimate shrinkage increased with the addition of CKD as replacement of cement. Addition of fine CKD causing retention of more water and drying from bulk resulted in higher shrinkage. Additionally, reduction of cement due to replacement by CKD made availability of more unreacted water in the mix for shrinkage. Also reduced hydration products due to decreasing cement delayed disruption of capillary structure that allowed longer evaporation and higher shrinkage. However, in the Group-2 and Group-3 mixes using RHA, either alone or in combination with spent foundry sand as fine aggregate, the ultimate shrinkage decreased with increased CKD content in the mixes. In the Group-2 and Group-3 mixes, use of RHA having a highly porous structure acted as an internal reservoir that provided an internal source of water. Any loss of moisture due to drying was compensated by redistribution of water from porous structure of RHA resulting into lower shrinkage.

5.2.8 Permeability

Permeability of all the CLSM mixes was close to the range 10^{-5}-10^{-4} cm/sec specified for most excavatable CLSMs, compacted granular fills and clean sand with good drainability.

Permeability decreased with addition of CKD as replacement of cement in Goup-1 CLSM mixes that had spent foundry sand with low porosity as fine aggregate. Fine CKD particles causing refinement of pore structure of the hardened CLSM resulted in reduced hydraulic conductivity. However, Group-2 and Group-3 mixes using highly porous RHA as fine aggregate showed higher permeability upon addition of CKD. In Group-2 and Group-3, addition of CKD as replacement of cement led to lesser hydration/pozzolanic activity that resulted into decreased hydration products and caused more porosity or higher permeability.

5.2.9 Mineral phases and microstructure analysis

Mineral phase identification through XRD process presented prominent phases of quartz (Q), calcite (C), hydration products such as ettringite (E), portlandite (CH), clinozoisite (Cl), gismondine and gypsum (G) in the hardened CLSM mixes of different groups. Phases of hydration products ettringite, portlandite, gismondine and clinozoisite etc. indicated a strength activity relatable to the mixes having some cement content as binder. The phase composition for each group mixes remained similar qualitatively.

Phases such as calcite (C), calcium silicate hydrate (CSH), calcium hydroxide (CH) and ettringite (E) were identified in FE-SEM images along with EDS scan results of CLSM mixes in different groups. Size and number of voids seen in the images related with porosity/permeability results. CLSM mixes with low CKD content or higher cement proportion showed more hydration products such as CSH, C and E. Compressive strength for the mixes related well to the presence of hydration products accordingly. Images of 100 % CKD mix showed no hydration products and only unreacted particles of mix materials which was indicative of the CKD's inert nature. Further, addition of CKD in CLSM mixes resulted in higher Si/Al ratios. Notably higher Si/Al ratio are known to reflect low strength of the mixes. The reducing compressive strength results for addition of CKD correlated well with general rising trend among majority of Si/Al ratios within the respective group mixes.

5.3 LEACHATE TOXICITY

Concentration of heavy metals namely, Pb, Cd, Cu, Cr, Zn, Ni, Ba, Li, Sr and Mg in the CLSM mixes of Group-1 and Group-3 covering use of all by-products were examined by Toxicity Characteristics Leachate Procedure (TCLP). Parametric values for some of heavy metals are according to USEPA TCLP limits for hazardous wastes. For some other metals the regulatory level is equal to 100 times the allowable concentration level either in 'Drinking Water Standards and Health Advisories' of the United States or 'Indian Standard Drinking Water Specifications'. This is with the presumption that the leachate is supposed to undergo a 100 times dilution before it reaches the drinking water level. The heavy metal concentrations in the leachate of CLSM mixes were within regulatory limits and therefore, all proposed by-products SFS, RHA and CKD in the development of CLSM were safe for use as backfill.

5.4 ECOLOGICAL ANALYSIS

Ecological analysis in terms of embodied energy (EE) and embodied carbon (ECO_2) of the CLSM mixes was done to ascertain the impact of utilizing by-products. Addition of CKD as replacement of cement led to reduced EE and ECO_2. This was attributed to EE and ECO_2 of the by-products being zero due to the fact that these are generated un-intentionally during the manufacturing process. The by-products replacing the cement or other natural materials having higher EE/ECO_2 coefficient reduced the ecological parameters. The mixes with 75 % CKD in all groups were more ecofriendly than conventional CLSM, concrete and compacted fill in terms of EE and ECO_2. The utilization of larger content of industrial by-products for the preparation of CLSM is recommendable to augment sustainability. Full benefit of the industrial by-products with respect to EE and ECO_2 shall be availed of, when the field application of such CLSM is adopted in locations near to the source of by-product generation. This will minimize EE/ECO_2 for transportation of by-products in addition to saving cost.

5.5 OTHER ASPECTS LIKE ADVANTAGES, CHALLENGES, FUTURE RESEARCH PROSPECTS

CLSMs because of its very low strength requirements, allow large scale use of by-products, making it environmentally advantageous. This helps sustainability in terms of lesser extractions of natural resources, less waste generation, reduced GHG emissions, lesser pressure on landfill spaces. Flowability of CLSM facilitates self-compaction, self-levelling and its placeability in congested places. It is hugely advantageous in terms of energy efficiency and time-efficiency. Due to early strength gain, the utility applications where CSLM is employed can be put into service early. CLSM allowing use of by-products also prove eco-friendly in terms of lowered embodied energy and embodied carbon. Low density of the CLSM due to use of by-products RHA and CKD can allow economic design of embedded utility elements and therefore is sustainable.

Lack of a standard mix design procedure makes adoption of CLSM a challenge. A large-scale project would require huge quantities of by-products which may involve many sources. By-products sourced from many quarters having different characteristics pose challenges in standardization of design procedure. The chemical composition of the by-products SFS, CKD and RHA need to be examined for each source as they vary for different sources. It is essential that the developed CLSM is safe with respect to leachate toxicity before using the by-products as constituents of CSLM. Arrangement of by-products involves logistical expenses and therefore, implementation of the study in the vicinity of the sources of by-products is recommended. Owing to the use of specialized techniques, cementing and other materials, higher initial cost of the CLSM compared to prevalent backfill options could be a deterrent for choice of CLSM as backfill in any project.

Future research could focus upon reduction of long setting time resulting due to use of the industrial and agro by-products in the present study. Long-term leaching behaviour assessment of the CLSM is important to ensure extended environmental safety of its application and needed to be taken up as further scope of work. Further, pond ash is a by-product from burning of coal as fuel in thermal power plants which is dumped in ash dykes spread over large area. Abundance of pond ash in thermal plants being a problem, future studies can include pond ash along with the by-products used in present study for development of CLSM. This would be helpful in giving solutions for handling huge quantities of pond ash stored in ash dykes waiting disposal. This would reduce pressure on existing ash dykes and demand for fresh dykes. CKD may contain soluble alkalis that can contribute to alkali-silica reaction (ASR) in the presence of reactive aggregates. Therefore, the study of ASR and solutions to tackle it may be taken up in the scope for future work. Permeability results for mix S-CKD-25 was anomalous/inconsistent with the trend, therefore permeability for Group-1 mixes may be further studied as future scope of work.

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