

OPTIMIZATION OF CONTROLLED LOW STRENGTH CONCRETE USING GGBS, PFA AND LIMESTONE DUST

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

**MASTERS OF ENGINEERING
IN
STRUCTURAL ENGINEERING**

Submitted by:
RAM GUPTA
(ROLL NO. 801122016)

UNDER THE GUIDANCE OF:

SHWETA GOYAL
Assistant Professor
Civil Engineering
Thapar University, Patiala

MANEEK KUMAR
Professor
Civil Engineering
Thapar University, Patiala

ROGER WEST
Associate Professor
Civil Engineering
Trinity College, Dublin

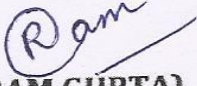
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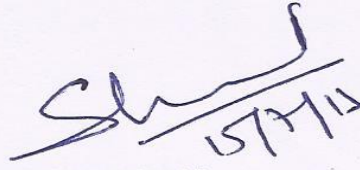
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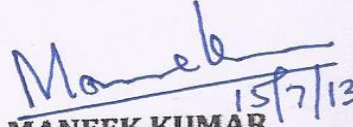
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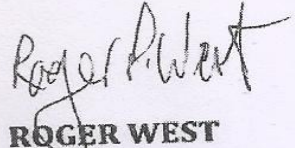

(RAM GUPTA)
 Roll No.: 801122016


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SHWETA GOYAL
 Assistant Professor
 Civil Engineering
 Thapar University, Patiala


MANEEK KUMAR
 Professor
 Civil Engineering
 Thapar University, Patiala


ROGER WEST
 Associate Professor
 Civil Engineering
 Trinity College, Dublin


NAVEEN KWATRA
 Chairman, Board of studies
 Department of Civil Engineering
 Thapar University, Patiala

COUNTERSIGNED


S. K. MOHAPATRA
 Dean, Academic Affairs
 Thapar University, Patiala

ABSTRACT

A Controlled Low Strength Material (CLSM) is a highly flowable self-compacting material which is primarily composed of sand, cement, water and other filler materials. It is principally used as a replacement for soil backfill. The purpose of this project was to optimise the mixture proportions for performance using various fillers and cementitious materials such as GGBS, PFA and limestone dust. The recycling of these waste materials contributes to construction sustainability. The mixes must possess the consistency, flowability and strength which is required for CLSM. This was achieved through trial mixing, where derivation of new mixes is based on the performance of previous pours. To investigate the performance of the mixes derived, tests for flowability, density and compressive strength were carried out.

It was found that the cement/GGBS CLSM mixes could not demonstrate the highly flowable and consistent mixes with high water/fines to achieve the required low strength of not more than 2MPa at 28-days. To rectify this, ternary mixes were derived by incorporating PFA and limestone dust with cement/GGBS mix. The optimum pour with regards to both fresh and hardened properties was found to be the cement/GGBS/limestone dust, which consisted of the lowest cement contents in the range of 15 – 20 kg/m³. By replacing the sand content with an appropriate content of PFA or limestone dust, an improvement in the flowability of the pours was achieved. The cement/GGBS/PFA mixes did not comply with the hardened state properties as PFA contributed in long-term strength.

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CHAPTER 1 - INTRODUCTION

1.1 GENERAL

Controlled Low-Strength Material (CLSM) is a cementitious fill that is in a flowable state at the time of placement and has limited compressive strength to facilitate subsequent excavation. CLSM is also known as flow-crete and controlled density fill as well as by various proprietary names. The material has gained appreciable recognition in the USA and Canada as a fill material because of its inherent advantages. These include flowing placement without segregation, self-consolidation, controlled density, controlled strength, ease of excavation, and economy.

Development of CLSM has centered around mixtures using a sand filler. The inter-particle voids are slightly over-filled with a fluid paste composed of cement and water, with the possible addition of fly ash. Components of the paste are varied in quantity to achieve the required performance in terms of strength development, self-consolidation, flow behaviour characteristics, durability, economy and ease of removal.

Overseas experience has shown the sand filler mixtures to have performed well, giving all the properties desired. It may be difficult to achieve satisfactory flowability and there may be severe bleeding in cement-sand slurries –although fly ash can be of assistance in obtaining properties of flowability with reduced bleeding.

From the above description, it can be seen that CLSM is a cementitious material which can be mixed, transported and delivered using normal ready-mix operation techniques and processes. The material does not look like concrete but it performs in a similar manner since it has cementitious properties and, with time, will become quite hard. However, the latter must be controlled so that it does not

become too hard. As with any concrete, strength is influenced by the quantity of water and cement. Very high water content (300 to 450 kg/m³) and very low cement content (25 to 100 kg/m³) are quite normal for CLSM. Fly ash, sand and, in some cases, coarse aggregates, are selected for their ability to flow rather than for their contribution to strength properties. This implies that sand not suitable for regular concrete may perform quite well in CLSM. Indeed, sands with as much as 30% fines have proven satisfactory. Control of the material on site is best achieved by a flow test. A cylinder or cone is placed on a flat hard surface and filled with the flowable mix. When the mould is lifted, the material will spread on the flat surface. If the measured spread of the CLSM reaches the predetermined distance, the mix is considered to have acceptable flow.

1.2 APPLICATIONS

CLSM is ideal for use in any backfilling operation where it is important to minimise settlement or where there is restricted access for compaction equipment. It is also advantageous for backfilling excavations in soils that are prone to collapse when normal compaction equipment is used. Typical applications are:

- backfilling utility trenches;
- filling abandoned underground structures, eg tanks, sewers, tunnels, etc;
- backfilling bridge abutments and retaining walls;
- most situations where soil backfill is required.

Where backfill may have to be excavated at a later date, the strength of CLSM must be limited. Strengths up to 2 MPa at 28 days can generally be excavated using normal construction equipment. As CLSM is a highly fluid material, consideration must be given to the lateral pressure exerted during placement;

lightweight pipes, etc may need to be anchored to prevent flotation. CLSM mixes should be designed for the particular flowing characteristics required as well as the compressive strength necessary. As indicated previously, aggregates are chosen more for their compatibility with the CLSM's flowing characteristics than their contribution to strength.

A wide range of fine aggregates including sands, gravels and quarry waste material can be used to produce satisfactory CLSM mixes. It is not necessary for aggregate to comply with AS 2758.1-1985. Aggregates should, however, be free of reactive or expansive materials. Coarse aggregates are not normally included in CLSM. Types GB or GP cement in accordance with AS 3972 can be used in the production of CLSM. Where fly ash is used to improve flowability it should be noted that early strengths will be reduced. Maximum 28-day strength of 0.5 MPa is suggested where future hand excavation is likely and 1.5-2 MPa for mechanical excavation. Slumps that will suit most applications of CLSM are around 200 mm. Suggested criteria for CLSM mixes are given in table 1.1.

Table 1.1 Suggested criteria for CLSM mixes

Use/application	Criteria
General purpose backfill	Easy excavation required. Early strength not critical. High degree of flowability. 28-day strength \leq 0.5 MPa.
Roadway Trench Backfill	High early bearing strength required. Good flowability. 28-day strength 1.5 to 2 MPa.
Structural Backfill	Good flowability. 28-day strength to engineering requirements.

CHAPTER 2 – LITERATURE REVIEW

Sustainability is important to the well-being of the planet, continued growth of a society, and human development. Concrete is the most widely used construction materials in the world. However, the production of Portland cement, an essential constituent of concrete, leads to the release of significant amounts of CO₂, a greenhouse gas (GHG); production of one ton of Portland cement produces about 850kg of CO₂ and other GHGs. The environmental issues associated with GHGs, in addition to natural resources issues, will play a leading role in the sustainable development of the cement and concrete industry during this century.

To build structures and infrastructures that are cost-efficient, environmentally friendly, and durable, the impact of the building materials on local and worldwide air conditions must be examined (McDonough et al, 1992). At the current rate of increase of cement production (USGS 2006, 2007), worldwide cement production is expected to rise from about 2.5 billion tones in 2006 to about 5 billion tones by 2020. Thus, CO₂ emissions caused by Portland cement production are expected to rise by 100% from the current level by 2020. For each metric ton of Portland cement clinker, 1.5 to 10 kg of NO_x is also released into the atmosphere. If the challenges associated with reducing CO₂, NO_x, and other GHGs are to be met, then the concrete industry must develop other materials to replace Portland cement (Naik et al, 2008).

Therefore, supplementary cementing materials, which are waste/co-products from other industries such as fly ash, limestone dust and ground granulated blast-furnace slag should replace larger amounts of Portland cement in concrete. However, before any construction occurs, all aspects of the building materials to be used should be evaluated. The use of blended cements and organic chemical admixtures must be significantly increased for sustainability of the cement and concrete industries.

A proper disposal of waste materials that are produced from various industries is a serious problem in many countries. Generation of industrial waste materials and by-products is increasing as a result of industrialization as is the need for higher amounts of raw materials and fuel to accommodate the rapid increase in the world's population.

This obviously causes many environmental problems in the form of waste generation and raises the potential to contaminate water, air and soil resources. The safe disposal of waste is costly, and there is a lack of disposal sites that are suitably designed to handle such materials without causing detrimental effects on the environment. Therefore, in recent years, research has been directed towards finding alternative methods of utilizing waste materials and industrial by-products, where their harmful effects are minimized or even eliminated. The construction industry is one of the areas where the safe use of waste materials could have a promising future (Taha et al. 2005).

A controlled low-strength material (CLSM) is a self-compacted, cementitious material used primarily as a backfill as an alternative to compacted fill. Several terms are currently used to describe this material, including flowable fill, unshrinkable fill, controlled density fill, flowable mortar, plastic soil-cement, soil-cement slurry, and other various names. Controlled low-strength materials are defined by ACI 116R as materials that result in a compressive strength of 8.3 MPa (1200 psi) or less. Most current CLSM applications require unconfined compressive strengths of 2.1 MPa (300 psi) or less at 28 days. This lower-strength requirement is necessary to allow for possible future excavation of CLSM. It costs more per cubic metre when compared with conventional soil backfill; however its advantages result in lower in-place costs. (ACI Committee, 1999)

The primary application of CLSM is as a structural fill or backfill in lieu of compacted soil. As CLSM needs no compaction and can be designed to be fluid, it

is ideal for use in tight or restricted-access areas where placing and compacting fill is difficult. If future excavation is anticipated, the maximum long-term compressive strength should generally not exceed 2.1 MPa (300 psi). The following applications are intended to present a range of uses for CLSM.

2.1 APPLICATIONS OF CLSM MIXES:

2.1.1 Backfills :

CLSM can be readily placed into a trench, hole or other cavity. Compaction is not required; hence the trench width or size of excavation may be reduced. Granular or site excavated backfill, even if compacted properly in the required layer thickness, may not achieve the uniformity of CLSM (Siddique, 2009).

2.1.2 Structural fills:

CLSM may be used for foundation support. Compressive strengths may vary from 0.70 to 8.27MPa depending upon its application. In case of weak soils, it can distribute the structure's load over a greater area. For uneven or non-uniform sub-grades under foundation footings and slabs, CLSM can provide a uniform and level surface (Siddique, 2009).

2.1.3 Conduit bedding:

CLSM provides an excellent bedding material for pipes, electrical, telephone and other types of conduits. The flowable characteristic of the material allows the CLSM to fill voids beneath the conduit and provide a uniform support. CLSM can be designed to provide erosion resistance beneath the conduit. Encasing the entire conduit in CLSM also serves to protect the conduit from future damage. If the area around the conduit is being excavated at a later date, the obvious material change in CLSM versus the surrounding soil or conventional granular backfill could be recognized by the excavating crew, alerting them to the

existence of the conduit. Coloring agents have been used in mixtures to help identify the presence of CLSM (Siddique, 2009).

2.1.4 Erosion control:

It has been proven through laboratory and field performances that CLSM resists erosion better than many other fill materials. Tests comparing CLSM with various sand and clay fill materials showed that CLSM, when exposed to a water velocity of 0.52 m/s, was superior to the other materials, both in the amount of material loss and suspended material. Rip rap for embankment protection and installing basins below dam spillways are often filled with CLSM to hold rock pieces in place and prevent erosion. Flexible fabric mattresses used along embankments for erosion protection are filled with CLSM to provide strength and weight to the fabric revetments. In addition to providing erosion under culverts, CLSM is used to fill voids under pavements, sidewalks, bridges and other structures where natural soil or non-cohesive granular fill has eroded away (Siddique, 2009).

2.1.5 Void filling:

In filling old tunnels and sewers, it is important to use a highly flowable mixture. A constant supply of CLSM will help keep the material flowing and make it flow greater distances. Unwanted basements are often filled-in with CLSM by pumping or conveying the mixture through an open window or doorway. CLSM has been used to fill abandoned underground tanks.

2.1.6 Groundwater cutoff:

CLSM mixes are extensively used as a means of groundwater cut off. It can control seepage beneath dams and contain polluted groundwater which arises from the presence of insanitary landfills. CSLM can provide this function due to its low permeability. Usually, bentonite, which is a sodium clay that expands when wet, is added to the CLSM mix which lowers its permeability significantly to the order of

10⁻⁹m/s. Essentially, the 'flowcrete' acts as barrier against contaminated water (Siddique, 2009).



Figure 2.1 - Flowing down the chute of a ready mix truck, CLSM quickly fills this deep utility trench.

2.1.7 Pile driving:

The objective with which the CLSM mix is tried in this project will be applied in driving the sheet pile through the fill for which the strength should be less than 1MPa at 7-days.

These are several advantages and disadvantages of using CLSM when compared to using soil as a backfill. These advantages include:

2.2 ADVANTAGES:

- **Can be excavated:** CLSM having compressive strengths of 1MPa to 2MPa is easily excavated with conventional digging equipment yet is strong enough for most backfilling needs.
- **Easy to place:** Depending on the type and location of void to be filled, CLSM can be placed by chute, conveyor, pump, or bucket. As CLSM is self-leveling, it needs little or no spreading or compacting. This speeds construction and reduces labor requirements.

- **Requires less inspection:** During placement, soil backfill must be tested after each lift for sufficient compaction. CLSM self-compacts consistently and does not need this extensive field testing.
- **Reduces excavating costs:** CLSM allows narrower trenches because it eliminates having to widen trenches to accommodate compaction equipment.
- **Does not settle:** CLSM does not form voids during placement and will not settle or rut under loading. This advantage is especially significant if the backfill is to be covered by a pavement patch. Soil or granular fill, if not consolidated properly, may settle after a pavement patch is placed and form cracks or dips in the road.
- **Versatile:** CLSM mix designs can be adjusted to meet specific fill requirements. Add more water to improve flowability. Add more cement or fly ash to increase strength. Admixtures can be added to adjust setting times and other performance characteristics. Adding foaming agents to CLSM produces a lightweight, insulating fill.
- **Strong and durable:** Load-carrying capacities of CLSM typically are higher than those of compacted soil or granular fill. CLSM also is less permeable, thus more resistant to erosion. For use as a permanent structural fill, CLSM can be designed to achieve 28-day compressive strengths as high as 8MPa.
- **Improves worker safety:** Workers can place CLSM in a trench without entering the trench, reducing their exposure to possible cave-ins.
- **Makes use of a waste by-product:** Fly ash is a by-product produced by power plants that burn coal to generate electricity. CLSM containing fly ash benefits the environment by making use of these industrial waste materials. Similarly for other by-products as GGBS and limestone dust.

2.3 DISADVANTAGES:

- **Unreliable strength acquisition:** A CLSM mix has very low 7-day strength of 1 MPa, which is very difficult to predict.

- **High segregation:** The mixes are highly prone to segregation when not properly designed as they have a high water/fines ratio and low cement content.
- **Non-Uniformity:** Can be hard to mix uniformly due to high water content.
- **Bleeding:** High degree of bleeding leading to volume loss and inaccurate finish levels.
- **Shrinkage:** Very high degree of shrinkage when high water/cement ratio used.
- **Mix design is difficult to achieve sufficiently low strength while maintain cohesiveness.**

With the recent economic downturn worldwide, the construction industry has recognized the importance of sustainable development. With regard to CLSM, one can efficiently use by-products and waste materials within the mix to reduce the cost of its production (Nataraja et al, 2007). The efficient disposal of waste can be costly and can have negative impacts on the environment due to the generation of this waste. As a result of this, research has been carried out in the last number of years on ways to make use of these waste materials. It has been found that the construction industry is a sector in which the safe use of these by-products may have considerable commercial potential (Taha et al, 2006).

The proper disposal of waste materials that are produced from various industries is a serious problem in many countries. The generation of industrial waste materials and byproducts is increasing as a result of industrialization as is the need for higher amounts of raw materials and fuel to accommodate the rapid increase in the world's population. This obviously causes many environmental problems in the form of waste generation and raises the potential to contaminate water, air and soil resources. The safe disposal of waste is costly, and there is a lack of disposal sites that are suitably designed to handle such materials without causing detrimental effects to the environment. Therefore, in recent years, research has been directed towards finding alternative methods of utilizing waste materials and industrial by-products, where their harmful effects are minimized

or even eliminated. It has been well known, for more than three decades, that the use of industrial by-products such as fly ash (FA), silica fume, pulverized-fuel ash and granulated blast furnace slag (GGBS) as a partial replacement of cement improves the durability of concrete structures and may also enhance the properties of both fresh (e.g. workability, bleeding, etc.) and hardened (e.g. strength) concrete. This is well documented in various codes of practice. Another application where such materials can be re-used beneficially is as flowable fills or controlled low strength materials (CLSMs). Originally a CLSM was slurry consisting of a mixture of cement, sand, water and FA. Since sand and cement are the major components of CLSM, replacing the cement and/or natural sand with waste materials is an attractive beneficial reuse option and helps to keep the strength down (Alnuaimi et al, 2006).

CLSM mixes should be designed for the particular flowing characteristics required as well as the compressive strength necessary while remaining cohesive and stable in the fresh state. The aggregates are chosen more for their compatibility with the CLSM's flowing characteristics than their contribution to strength. A wide range of fine aggregates including sands, gravels and quarry waste materials can be used to produce satisfactory CLSM mixes. It is not necessary for aggregates to comply with codes. Aggregates should, however, be free of reactive or expansive materials. Coarse aggregates are not normally included in CLSM as they impart strength to the CLSM mix. Where fly ash is used to improve flowability it should be noted that early strengths will be reduced. Maximum 28-day strength of 0.5 MPa is suggested where future hand excavation is likely and 1.5–2 MPa for mechanical excavation. A flow diameter in the Flow Table test should be between 600mm to 700mm.

2.4 PRIMARY CONSTITUENT

Water is also present in the mix. When the clinker is in contact with water, a series of chemical reactions take place. Hydration occurs where a Calcium-

Silicate-Hydrate (CSH) gel forms rapidly on the surface of the cement grains and begins to bind the aggregates together. (Pavia, 2012). The water is also necessary to achieve adequate flowability and workability. Water contents in CLSM mixes vary from 190 to 340kg/m³. However, in the presence of fly ash, the water content may be reduced as the PFA improves the flowability of the material and reduces the water demand.

The most common fine aggregate found in CLSM is sand. Sand makes up approximately 75% of the CLSM. Its proportion in the mix can vary between 1200kg/m³ and 1840kg/m³ (Gabr et al, 1999).

Course aggregates such as gravel are not commonly used in CLSM mixes, as they provide strength to the concrete. However, for CLSM mixes one wants to deliberately make concrete weak, so the use of course aggregates will not be needed.

2.5 PULVERISED FLY ASH

The most common by-product found in CLSM mixes is pulverized fuel ash (PFA). PFA can be defined as “the finely divided residue resulting from combustion of ground or powdered coal” (ACI Committee, 1999). It is essentially a by-product of a coal fired electric generating plant. As well as providing environmental advantages, PFA, as in Figure 2.2, will also improve the performance and quality of the CLSM due to the rounded particle shapes of the PFA which improves the flowability of the material. The typical chemical composition of Class F ash is thus:

SiO ₂ > 50%	Al ₂ O ₃ 20 - 30%	Fe ₂ O ₃ < 20	CaO < 5%
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And of Class C ash is

$\text{SiO}_2 > 30\%$	Al_2O_3 15-25%	$\text{Fe}_2\text{O}_3 < 10$	$\text{CaO} = 20-30\%$
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(Mindess et al, 2003).

PFA looks like cement to the naked eye if slightly darker but it is slightly finer than cement, and has a lower density, where the specific gravity for PFA ranges from 1.9 to 2.4 whereas for cement, it is 3.15 approximately.



Figure 2.2 -Pulverised Fuel ash. (Concrete basics, 2012)

Although the chemical constituents compound of PFA are similar to that of cement but not in the same proportions, one cannot however completely replace the cement content with PFA. The reasons for this is that once the Portland cement mixes with water, a process called hydration starts; this is where calcium-silica-hydrate (C-S-H) gel forms rapidly on the cement grains. This is the component that binds the aggregates together and provides the concrete with its strength. As well as this, Portlandite (Calcium Hydroxide) is also formed during the hydration of the cement. It is the constituent that the PFA reacts with to form additional C-S-H gel (Pavia 2012). In the UK, PFA can replace the cement content by up to 40% in some cases. However, hydrated PFA is not as strong as cement on a mass for mass basis i.e. one would not obtain the same compressive strength if

one replaced 100kg of cement with 100kg of PFA. This means a significant amount of additional PFA would need to be added to obtain the same strength (Day, 2006). From this conclusion, one can see that there is a difference between water/cement ratio and water/binder ratio. For mix designs containing PFA, Balendran (1995) uses cementing efficiency in the form of a 'k factor' to incorporate PFA in the water/cement ratio. The following equation is then defined:

$$w / b = w / (c + kP)$$

where,

w = free water content.

b = binder content.

c = Portland cement content.

P = pulverised fuel content.

k = reduction factor.

For this equation, both mixes (i.e. one with cement only and one with cement and PFA) have a similar target strength and workability. Regarding the k factor, in a paper published by the Department of Environment in the UK in 1988, the reduction factor k is taken to be 0.3. However, a paper by China Light and Power takes the k factor to be 0.75 when there is 25% PFA within the mix, and takes the k factor to be 0.3 when there is 70% PFA content, though clearly in this case much of the PFA acts as a filler and not a cementitious material (Balendran, 1995).

There are several advantages of using PFA within a CLSM mix; replacing the cement content will reduce the cost of the mix, but there is also an associated reduction in early strength of the CLSM as the hydration process is retarded by the presence of PFA. Also there is less cement in the concrete which means the

heat of hydration is less. This reduced heat generation would count as an advantage while pouring CLSM in a hot climate. (Day, 2006).

Usually, it can be difficult to achieve good flowability in a mix without the occurrence of heavy bleeding, however with the addition of fly ash to the mix, it improves flowability, reduces bleeding and aids in pumpability as it also acts as a fine aggregate. This additional fineness provides more cohesion and stability to the mix because of the greater surface area of the finer particles which absorbs the water. There are essentially two types of PFA that are used in concrete mixes; class C is a material that has little or no cementitious characteristics, so it basically acts as a filler within the mixes whereas the Class F is a true pozzolanic material that has cementitious properties and because of this it is more predominantly used (Day, 2006).

The introduction of PFA will reduce the early strength of the CLSM because the rate of hydration of PFA is slower. This suppresses the initial reaction of C_3S (alite), which is the compound that provides a significant proportion of early age strength to the concrete, which can be seen in figure 2.3. However, the presence of PFA will also increase its long term strength meaning the cement content may also be reduced accordingly. This happens because the PFA consumes the weak CH over time and replaces it with hard stable calcium silicates and aluminium hydrates. (Gabr et al, 1999). According to the European standards IS EN206, they suggest a 10% increase in the 28 day strength of a Portland cement/PFA mix.

Flowability is an important characteristic for CLSM mixtures; this is because one wants the mix to be able to flow into the available space but, with the presence of PFA in the mix it was found that a desired flow can be achieved with a lower water/cement ratio. This is due to the reduced water demand provided by the presence of the PFA and by the spherical nature of the PFA particles (Nataraja et al, 2007).

The compounds that provide a significant proportion of strength to the concrete can be seen in the figure 2.3. However, the presence of PFA will also increase its long term strength meaning the cement content may also be reduced accordingly.

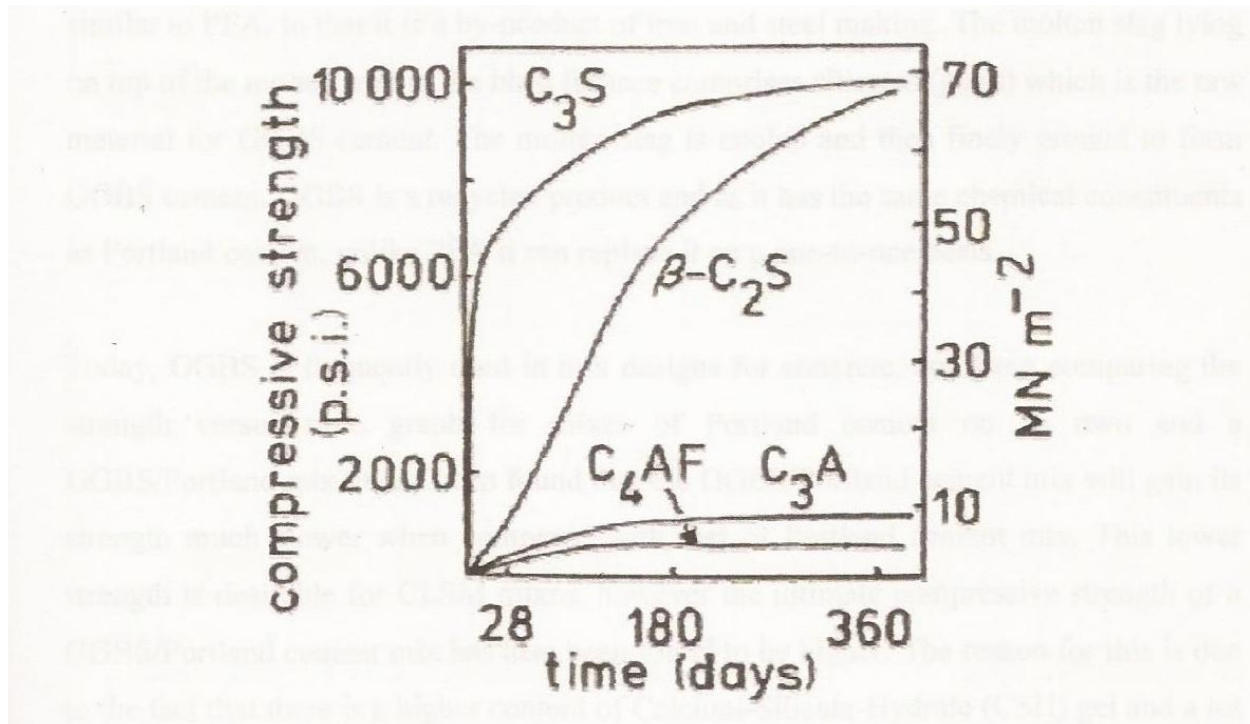


Figure 2.3 - Constituents contribution to strength over time (Pavia, 2012).

Compressive strengths of CLSM are usually limited to 2MPa to allow for future excavation. It is observed that for CLSM mixes consisting of PFA/cement, strength rises as age increases, however after 7 days the increase in strength is only marginal due to the reduced pozzolanic activity of the cementitious materials (Nataraj, 2007).

Depending on whether PFA is a locally available waste product material, it can play a significant role in contributing to sustainability. Using PFA in concrete saves energy and reduces CO₂ emissions that are required to produce Portland cement. One ton of Portland cement (PC) requires about 4 Giga Joules of energy

and each ton of PC emits approximately 850kg of CO₂. So, one can say that every ton of PC replaced with PFA saves about 850kg of CO₂ from being released into the atmosphere. Ready mix concrete producers can take advantage of the locally available material such as quarry dust and PFA, which can discard the need to import expensive lightweight aggregate and reduce the carbon footprint of Controlled Low Strength Material (ScotAsh, 2005).

2.6 GROUND GRANULATED BLAST FURNACE SLAG

Ground granulated blast-furnace slag (GGBS) can also be used in CLSM in combination with other cementitious materials such as Portland cement. GGBS is similar to PFA, in that it is a by-product, but of iron and steel making. The molten slag lying on top of the molten iron in the blast furnace comprises silicates (glass) which is the raw material for GGBS cement. The molten slag is cooled and then finely ground to form GGBS cement. GGBS is a recycled product and as it has the same but not identical chemical constituents as Portland cement, and unlike PFA it can replace it on a one-to-one basis.

GGBS is frequently used in mix designs for concrete, and from comparing the strength versus time graph for mixes of Portland cement on its own and a GGBS/Portland mix, it has been found that the GGBS/Portland cement mix will gain its strength much more slowly when compared with that of Portland cement mix. This lower strength is desirable for CLSM mixes, however the ultimate compressive strength of a GGBS/Portland cement mix has also been found to be higher. The reason for this is due to the fact that there is a higher content of Calcium-Silicate-Hydrate (CSH) gel and a lot less Calcium Hydroxide (lime) in the resulting concrete.

The CSH gel is the binder that holds the aggregates and provides the concrete with its strength whereas the lime provides a small amount of strength to the

concrete. The GGBS consumes this weaker CH over time and replaces it with more stable CSH gel. For this reason the 28 day cube strength may not be an accurate reflection of its long term strength, so a 56 day cube test is recommended (Taha, 2006). Similarly with PFA, by replacing the content of Portland cement, it will reduce the amount of CO₂ which would need to be emitted when producing Portland cement. The job requirements may allow the need for Portland cement to be eliminated completely from the mix. In *figure 2.4*, a graph compares the compressive strength against time of a Portland cement mix and a 50/50 mass proportion Portland/GGBS mix. The data was provided by EcoCem (an Irish company supplying GGBS to the market). Note: the strength vs. time graph for Portland/PFA mixes would be similar to that of the Portland GGBS mix.

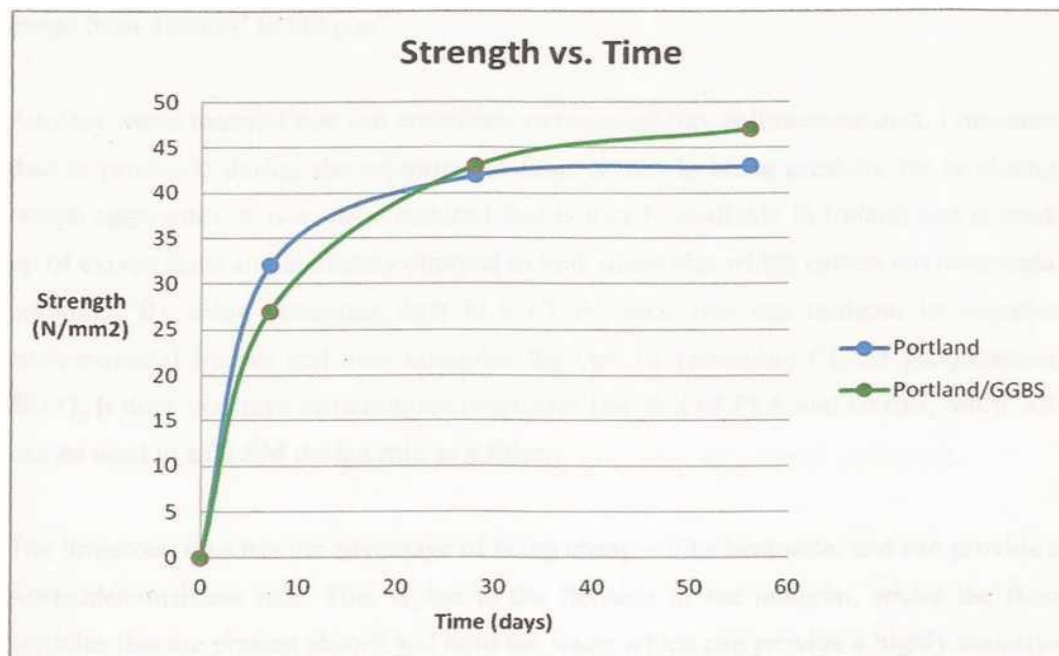


Figure 2.4 - Strength vs. Time for Portland and Portland/GGBS mixes

2.7 LIMESTONE DUST

Another waste material that can contribute to sustainability is limestone dust. Limestone dust is produced during the rupturing of large stones in stone crushers for producing coarse aggregates in quarrying. It is a waste material that is locally available in Ireland and is made up of excess fines and is usually dumped in bulk quantities which causes environmental pollution. By using limestone dust in a CLSM mix, one can mitigate its negative environmental impact and also minimize the cost of producing CLSM (Naganathan, 2011). It does not have cementitious properties like that of PFA and GGBS, but it still can be used in a CLSM design mix as filler.

The limestone dust has the advantage of being cheap and can provide a workable/consistent mix. This is due to the fineness of the material, where the finer particles that are present absorb and hold the water which can provide a highly cohesive mix. The fineness of limestone dust is discussed in Chapter 3. As the limestone dust is not a cementitious material, it will not provide any additional strength to the mix in the long term though it does assist in early age strength by providing nucleation sites for hydration. However, in saying this, the paper published by Naganathan which analysed the effect of limestone dust within a CLSM mix, concluded that with the addition of quarry dust, there is a slight increase in compressive strength. A reason for this may be because of the high percentage of silica present in the quarry dust, which may produce more C-S-H gel during hydration which increases the strength gain (Naganathan, 2011). Depending on the nature of the quarry dust obtained here in Ireland for the CLSM mix, the results may differ from this. As was mentioned previously, the flowability of CLSM is very important. It was found that mixes containing quarry dust can achieve a desired flow with a lower water/cement ratio when compared with that of mixtures containing sand. (Nataraja et al, 2007). A cement/limestone dust CLSM mix has a very flowability and can be poured at one place to fill the required area which removes the labour cost as seen in the figure 2.5.



Figure 2.5 - 'Cement/PFA CLSM mix' flowing down the chute of a ready mix truck

2.8 OTHER FILLER MATERIALS

An alternative to CLSM mixes is Foamed concrete which is expensive in comparison. The most basic definition of foamed concrete is that it is 'mortar with air bubbles in it'. The air content of foamed concrete may be up to 75% by volume. In general terms, foamed concrete can be described as a lightweight, free flowing material which is ideal for a wide range of applications. It can have a range of dry densities, typically from 400 kg/m³ to 1600 kg/m³ and a range of compressive strengths from 1 MPa to 15 MPa.

A successful CLSM mix using bentonite as workability agent was prepared at Trinity (2012). Bentonite, which is a fine material with a high water absorbing capacity, acts as an excellent workability agent where the optimum quantity found lies in the range 50 - 70kg/m³. Successful trial mixes were carried out when using bentonite which achieved flowability, consistency and strength requirement. But the major drawback of bentonite is that it could not be used for the project where high quantities of CLSM are required as it is prohibitively expensive. In this project other more economical materials will be considered.

CHAPTER 3 – METHODOLOGY

3.1 OBJECTIVE

The aim of this project is to optimise the mixture proportions for performance using various fillers and cementitious materials for CLSM. There is bulk GGBS produced in Ireland, over 400,000 tonnes was available in Ireland in 2008. The idea is to use the maximum amount of Ground Granulated Blast Slag (GGBS) and incorporate it with different filler materials so that the fresh and hardened state properties of CLSM are satisfied. A private construction firm in the West of Ireland contacted Trinity College and asked them to optimise specific mix designs for CSLM. Their use for the CLSM is that they are going to pour the material on site to stabilize the soil where they can drive piles within 7-days. As there are large volumes of this mix, the client wished it to be eco-friendly and economically viable.

For the fresh state of CLSM, it must possess sufficient flowability, consistency and density while avoiding heavy bleeding as well as any significant segregation. Flowability is particularly an important aspect of CLSM as it allows the materials to be self-compacting as well as readily flow into and fill a void. Flowability of a CLSM mix is measured through means of a flow table test; the adequate target flow from the test is between 600 and 700 mm. The fresh state density of CLSM mix is between 2100 to 2350 kg/m³.

In the hardened state, the material will have a target 7 day compressive strength of not more than 1MPa, which allows it to be excavated at a future date. The consistency of the mix is equally important. This aspect will heavily depend on the quantity of fines present in the mix. The finer a material is, the greater surface area-to-volume ratio, which means there is more surface area available to hold and absorb water in the mix. Fineness is measured in terms of surface area

per unit mass. The fineness of the cementitious and filler materials used in this project will be stated in the second part of this chapter.

The various mix combinations of the different filler and cementitious materials that had to be tested in conjunction with sand and water include:

Base mixes:

- Cement (CEM II A-L)
- Cement/GGBS

Ternary mixes:

- Cement/GGBS/PFA
- Cement/GGBS/Limestone dust

The above mixes were tested in the Trinity laboratory. The idea of the above is to use a high percentage of GGBS along with cement as a cementitious material so as to make this mix more environmentally friendly, with a basic CO₂ footprint. The PFA and limestone are to act as fillers, which try to make GGBS mixes more stable, consistent and flowable.

The performance of the CLSM was to be optimized by varying the quantities of each constituent. Numerous pours had to be carried out for each mix in which the performances and observations were to be recorded. As the pouring program proceeds, subsequent mix designs will then be varied depending on the results of the previous pour. This method of optimisation is known as “Trial mixing”.

“Trail mixes are the best way to determine how a given set of ingredients will achieve specific performance requirements” (Gao, 2012)

The results from this project can be useful to engineers/contractors considering applying CLSM for practical construction work.

3.2 MATERIALS

3.2.1 CEMENT

The cement is the material that provides the CLSM with its early age strength and also, due to its fineness, provides cohesion to the mix. The cement used for all the trial mixing was CEM II/A-L 42.5N complying with the specification for Portland-limestone cement in EN 197-1. A particle size distribution was done using a Malvern Mastersizer 2000. It is known as one of the most flexible and user-friendly particle sizing instruments available. The Mastersizer 2000 uses the technique of laser diffraction to measure the size of particles. It does this by measuring the intensity of light scattered as a laser beam passes through a dispersed particulate sample. This data is then analyzed to calculate the size of the particles that created the scattering pattern. The Blaine value for cement as measured was 3830 cm²/gm. A plot between particle size and percentage volume passing is plotted in Figure 3.1.

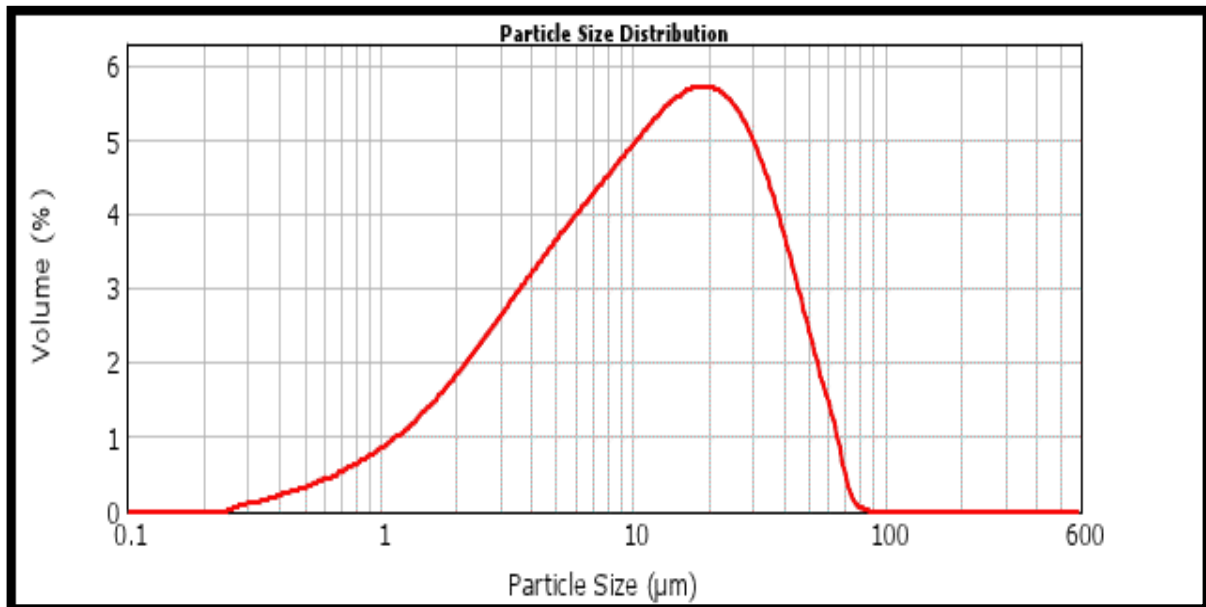


Figure 3.1 Plot between %volume passing and particle size for CEM II A-L cement

3.2.2 GGBS

Ground granulated blast furnace slag (GGBS) is a by-product from the steel industry. It is a cementitious material which can replace cement within the mix on a one-for-one basis. The GGBS used in from Ecocem Ireland. Ecocem's GGBS, produced in Dublin, meets the requirements of I.S. EN 15167-1, 2006. From the sieve testing, it was observed that the GGBS is not as fine as the cement or PFA and was highly variable in nature. The plot between particle size and percentage volume passing is given in figure 3.2, and it was tested by Ecocem in Europe.

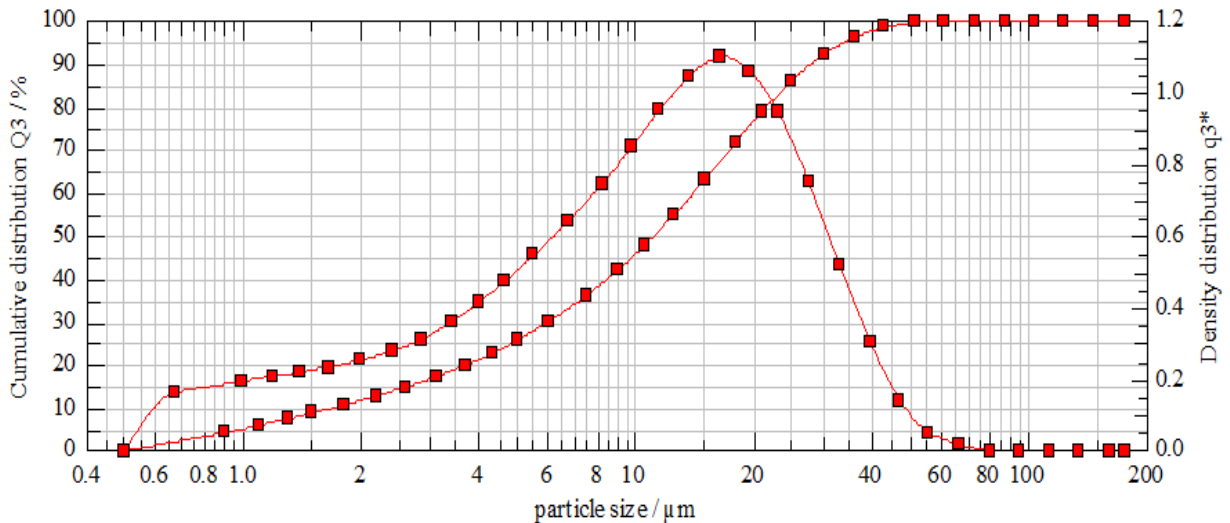


Figure 3.2 Plot between particle size versus % cumulative distribution and particle size versus density distribution of GGBS

3.2.3 PFA

Pulverised fuel ash (PFA), is commonly used in CLSM mixes. The major benefit for including PFA into CLSM is that it improves the flowability and reduces the effects of bleeding within the mix. It is also known to reduce the shrinkage and

permeability of the material. However the presence of PFA also can increase the long term strength of CLSM. The PFA used in this project is from Moneypoint Power Station, Co. Clare, Ireland. The plot between particle size and percentage volume passing is given in Figure 3.3, as produced by Irish cement.

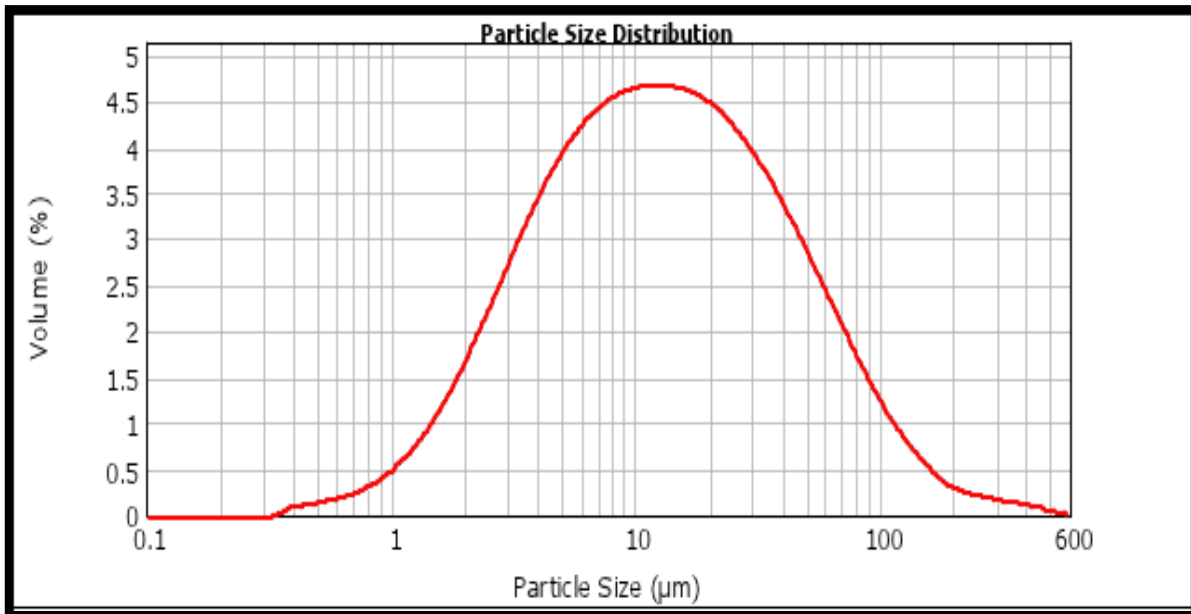


Figure 3.3 Plot between particle size versus % volume passing for PFA

3.2.4 LIMESTONE DUST

A by-product from quarrying, limestone dust will be used as a filler material in the CLSM. It is essentially an 'inert' material i.e. not cementitious. However it is known to increase the early age strength of the CLSM by a small amount due to the increased presence of silica if used in small dosages. The inclusion of Limestone dust can improve the consistency of the mix as the fine particles of the material absorb and hold the water. As seen from the sieve test, this is not as fine as the other materials. The particle size distribution of Limestone dust was established again, by the Malvern Mastersizer2000. The plot between particle size and percentage volume passing done by Irish cement is given in

Figure 3.4. It should be that in the plot there are two peaks, which Irish Cement believed to be as result of dolomitic or cherty limestone.

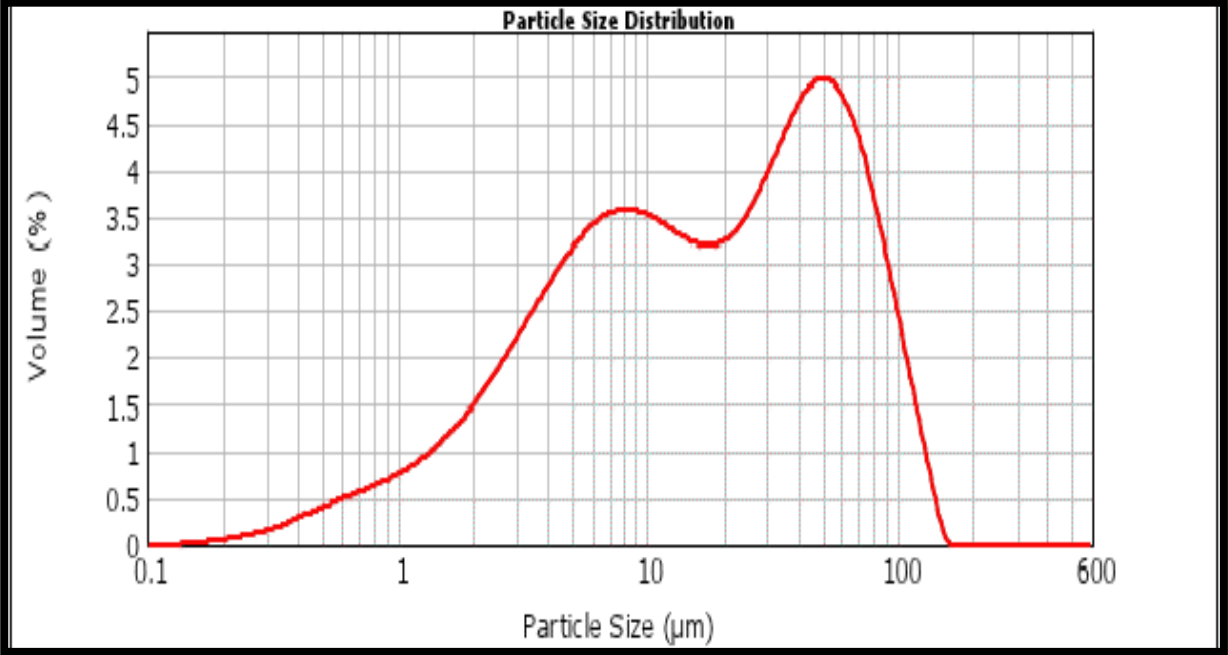


Figure 3.4 Plot between particle size versus % volume passing for Limestone dust

3.2.5 SAND

The sand acts as the fine aggregate within the mix, it makes up approximately 75% of the CLSM mixes where its primary function is to act as a filler. The sand used for all trial mixes was the same and was ordered from Banagher Concrete, Ireland. The sand available was medium sand. The sieve analysis of the sand was conducted in the Trinity Laboratory which is shown in table 3.1. The fineness modulus of sand was calculated to be 2.36. The moisture content for the sand used was 0.6%.

Table 3.1 Sieve analysis of sand

Sr. No.	Sieve Size.	Mass Retained (gm)	Percentage Retained	Cummulative Percentage Retained(C)	Percentage Passing (100-C)
1	4.75	63.5	6.35	6.35	93.65
2	2.36	35	3.50	9.85	90.15
3	1.18	132.5	13.25	23.10	76.90
4	600	128.5	12.85	35.95	64.05
5	300	282	28.20	64.15	35.85
6	150	327	32.70	96.85	3.15
7	Pan	31.5	3.15	$\Sigma = 236.25$	

3.2.6 COMPARATIVE ANALYSIS OF MATERIALS USED

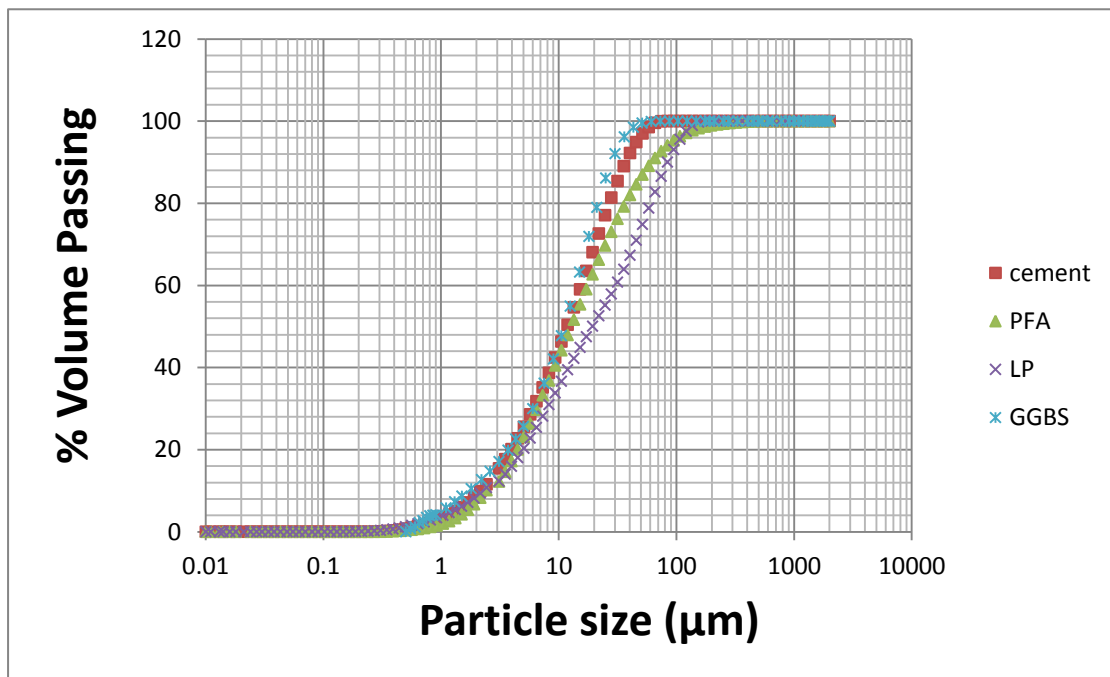


Figure 3.5 - Cumulative percentage passing graph for all materials

From the figure 3.5, seeing the cumulative particle size distribution graph of cement, PFA, GGBS and limestone dust one can say that the maximum particle size of PFA reached upto 522mm, which is highest when compared to other materials.

Sieve size of 0.1 μm to 1 μm

The limestone dust is shown to have 1.22% passing volume at 0.5 μm of sieve size, whereas cement, PFA and GGBS only have 1%, 0.5%, 0% volume passing respectively. The limestone dust have the most finer particles. At 1 μm sieve size, cement and limestone dust shows nearly the same percentage volume passing of 3.42% and 4%. Also PFA and GGBS have 2% and 5% volume passing. From the above observation, one can conclude that limestone has finer range of particle when compared to cement.

The GGBS have less finer range but high percentage passing till 1 μm sieve size. The PFA have the lowest percentage volume passing of 2 % under 1 μm sieve size which tells that PFA also does not have range of finer particle.

Sieve size of 1 μm to 10 μm

The PFA particle shows more percentage passing as compared to limestone dust, which indicates that PFA have more range of particles between 1 and 10 μm . The cement and GGBS have the highest percentage volume passing in this range of 47%. The limestone which shows more fineness in the sieve size range of 0.1 μm to 10 μm , now have the lowest percentage volume passing in this range of 35 to 38% when compared to other materials.

Sieve size > 10 μm

At the sieve size of 83 μm , the cement particles have 100% volume passing whereas PFA and limestone dust have 94% and 90% respectively. GGBS has 100% volume passing only at 73 μm sieve size. As concluded, it could be said that the GGBS has the smallest maximum particle size, followed by cement, limestone dust

and then PFA. The maximum PFA particle size is shown to be at 590 μ m but only has 6% volume passing between the sieve sizes of 83 μ m to 590 μ m.

3.3 EXPERIMENTAL TESTING

3.3.1 INTRODUCTION

The primary purpose of this project is to design a set of CLSM mixes using the materials mentioned with a compressive strength of not more than 1MPa at 7-day and 2MPa at 28-day. The mixes must also have sufficient flowability for a successful concrete tremie pipe (between 600mm and 675mm on a flow table test) operation as well as having moderate effects of bleeding and eliminating the occurrence of segregation. This objective will be achieved using trial mixes carried out in the Civil Engineering Laboratory at Trinity College, Dublin.

3.3.2 MIXING AND TESTING PROCEDURE

To achieve this objective, a set of trial mix proportions will be designed and poured. The mixing techniques for CLSM are very similar to those of conventional concrete.

The mixing of the CLSM will be carried out using a 0.02m³ drum mixer. The material quantities will be accurately measured on a weighing scale prior to mixing. The dry materials, which include the cement, sand and any other filler material, were placed into the mixer drum first and then blended for approximately 2 minutes to avoid any lumps. The water was slowly added to the mix. It may be necessary to add in only half the water content initially as the workability cannot be predicted. Then, based on further observations of the consistency and workability of the mix, additional water was added using a measuring beaker and the residual was recorded.

After the mixing procedure had been completed and all particles coated, the mix

was left untouched for 10 minutes to allow the cement to initially hydrate. Once this time has passed, the concrete was remixed prior to discharge and the testing can be carried out on the CLSM. As the slump of CLSM usually exceeds 210mm and collapses, the slump tests are not valid and will not be carried out. The flow table test will be a more appropriate test to investigate the flowability of the CLSM (IS EN 12350-5). The design criteria for a concrete tremie pipe requires a minimum of 600mm flow diameter (IS EN 1536). Therefore, design quantities of the materials will be modified to achieve sufficient flow diameters, where the target flows will be between 600mm and 675mm. The fresh density of the CLSM will also be measured using a cylindrical container of known volume (IS EN 1536).

In order to test the hardened properties of the CLSM, the fresh mix will be poured into eight 100mm x 100mm cube moulds. The cube specimens will then be kept at room temperature in the laboratory covered by a moist plastic cover sheet for 2 days to allow sufficient strength to develop to strike the cubes without damage due to their very low strength. The specimens will then be demoulded and placed in the curing tank at a constant temperature of 20°C. Two cube specimens will then be tested using a Zwick machine at 3, 7, 28 and 56 days to ascertain their compressive strengths where the average of each pair represents one valid result. The Zwick machine is set up for the rate of loading of 50 N/s and an initial load of 30N as the cube strengths are expected to be low.

Table 3.2 Initial mix constituents for base mix with pour volume of cement, sand and water

Constituents	Kg/m³	Kg/0.01 m³
Cement	250	2.5
Water	300	3
Sand	1650	16.5

No admixture was to be used for this project, though plasticizers, air-entrainment, self-compacting and foaming admixtures could all be incorporated, at additional cost, but is outside the scope of this project. It was not desired to use these for the site requirements which originated this research project.

CHAPTER 4 - BASIC MIXES

Prior to taking up this project, Darragh O'Rourke, who was a Master's student in Trinity College in 2012, had already carried out some preliminary cement/GGBS, cement/PFA, cement/ limestone dust testing in binary mixes only. Initially GGBS was chosen as a filler material however the mixes were not showing the flowability and cohesion needed. The GGBS did not mix well with sand and a lot of segregation and bleeding occurred. To rectify this O'Rourke used fly ash, limestone dust and bentonite individually as the workability agent, but only bentonite achieved sufficient flowability, consistency and compressive strength.

Now, the purpose of this project is to make GGBS mix work by incorporating limestone dust and PFA as ternary filler materials. The basic mixes in this chapter comprising cement and cement/GGBS mixes, will be monitored for fresh and hardened properties and, based on these observations, further mixes will be optimised. The objective is to control the behavior of the material by varying the constituent's proportions through trial mixing based on observations of preceding mixes.

4.1 BASIC CEMENT BINDER ONLY MIXES

Cement is the binder, a substance that sets and hardens independently and can bind other materials together. The cement used in this project is CEM II/A-L from Irish Cement Ireland complying with the specification in I.S EN 197-1, the Irish/European composition specification and conformity criteria for common cements.

The basic concrete mix with cement alone was tested just to understand the baseline properties of the mix without any filler material. The first pours were

derived and carried out on February 11, for varied cement contents as well as the water contents. The mix quantities can be seen in table 4.1.

Table 4.1 Mix proportions for mix C0, C1

Mix ID	Cement (kg/m ³)	Water (l/m ³)	Sand (kg/m ³)	W/C ratio
C0	250	300	1650	1.2
C1	140	240	1730	2.5

4.1.1 FRESH STATE OBSERVATION (C0, C1)

Mix C0 showed consistent workability with no bleeding. However, the mix had moderate flowability of 570 mm from the flow table test which is below the target minimum of 600 mm. The poor flowability of this mix was due to the absence of any filler material and low water quantity present. The fresh state density was measured for the mixes by filling a container of known volume with the mix and kept on vibrating table for 10 seconds, then weighed. As the weight and volume were known by now, thereby the density of the mixes was calculated. Mixes C0 and C1, fresh state density is shown in the figure 4.1.

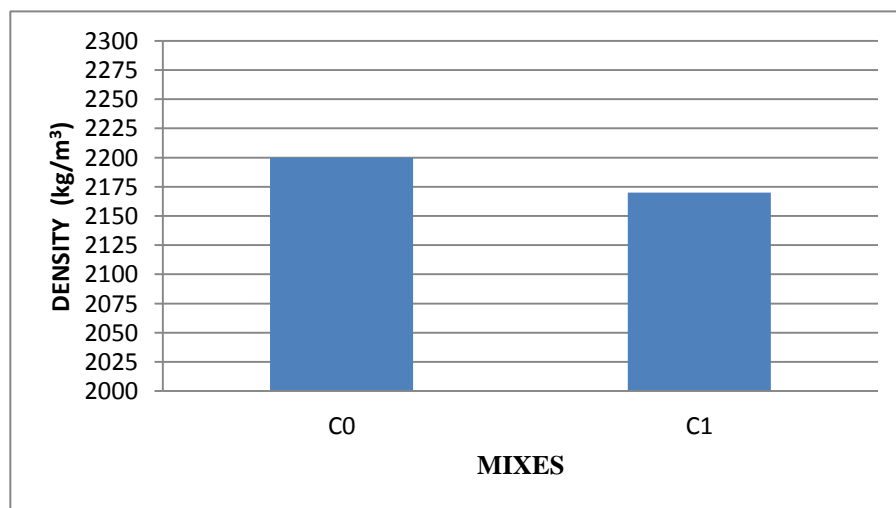


Figure 4.1 - Graph showing fresh state density for mixes C0, C1

For mix C1, the cement content is lowered to 100 kg/m³, the water to 250 l/m³ and the water/cement ratio was increased to 2.5. The water content was increased to understand how the mix performs at high water/cement ratios both in relation to stability and strength which would be required for the future pours. The fresh state observations showed that the flowability of the mix came back considerably to 520mm as well as the mix slightly segregating. From the graph in the figure 4.2, it can be seen as the cement content was lowered for mix C1, the flow table diameter was reduced to 520mm from 570mm (mix C0) which could be due to the less fines present in the mix.

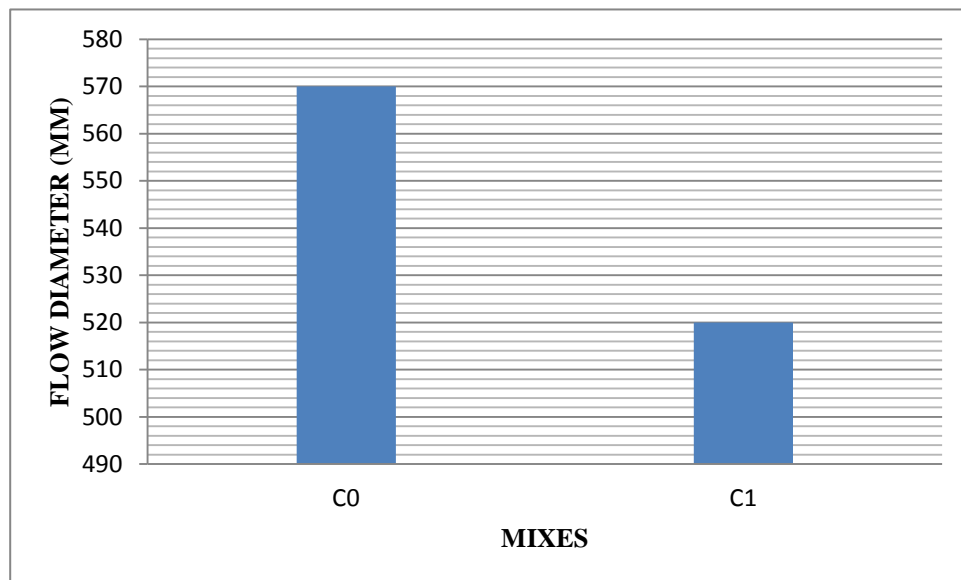


Figure 4.2 – Graph showing the flow table diameter (C0 and C1 mix)

Due to high water content, water did not mix well. Heavy and rapid bleeding was also observed which could be seen from water pooling that had occurred immediately after casting the cubes.

4.1.2 HARDENED STATE (C0, C1)

More often than not, designers want their concrete to be as strong as possible. However, the fundamental difference between CLSM and conventional concrete is

that there is a strict low limit on the compressive strength of CLSM. For example in order for this material to be excavated at a later date using standard digging equipment, the compressive strength cannot be greater than 2 MPa at 28-day. Knowing how these mixes develop their strength over time will allow the strength to be predicted at future excavations. The main function which determines the strength of the CLSM is the water to cement ratio. From previous work done by O' Rourke (2012), one knows that the target strength of not more than 2 MPa at 28 days lies in the water/cement ratio range between 2.0 and 3.0 for CEM II A-L cement alone.

Due to heavy bleeding and pooling on top of the cubes after they were cast, it was noticed that there was approximately 1-2 mm of settlement. This was observed two days after being cast when the water has evaporated from the surface. This occurs as the heavier materials in the cube specimen settle which causes the less dense, water to migrate to the surface. Once the bleed water evaporates from the surface, it leaves behind this reduction in volume.

For each mix eight cubes were cast during each pour with two being tested after 3,7,28 and 56 days. The results from the cube tests are summarised in table 4.2.

Table 4.2 Compressive strength of mix C0, C1

Mix ID	Cement (kg/m ³)	Water (l/m ³)	Water/ Cement ratio	3 day (MPa)	7 day (MPa)	28 day (MPa)
C0	250	300	1.2	9.6	11.30	18.00
				9.72	11.45	18.40
C1	100	250	2.5	0.7	1.07	5.75
				0.64	1.00	5.65

Once the cubes from pours C1 were demoulded, after 24 hours, the cubes were not struck perfectly and they were broken at the edges. As mix C1 had a high water/cement ratio which would be mandatory for future CLSM pours to attain

the required compressive strength, the period till striking was increased to 48 hours for all future pours. Due to the poor flowability of mix C1 and C0 it was not a surprise that the cubes were not entirely self compacting. Mix C0 had satisfactory fresh state properties, but the high compressive strength was expected due to the high cement content. Alternatively from day 3 to day 7 compressive strength of the C1 pours, one can see that they are in the range of the target strength of less than 1 MPa at 7 day, but had no workability whatsoever. A day 3 cube specimen, after testing, can be seen in plate 4.1.



Plate 4.1 - Rough surface of cube specimen C1 after cracking

The water/cement ratio, 1.2 for C0 mix was raised to 2.5 for C1 mix, the variation in strength development for both mixes can be seen in figure 4.3. The variation in strength is high as for mix C1, it failed for consistency and lot of unmixed water was present.

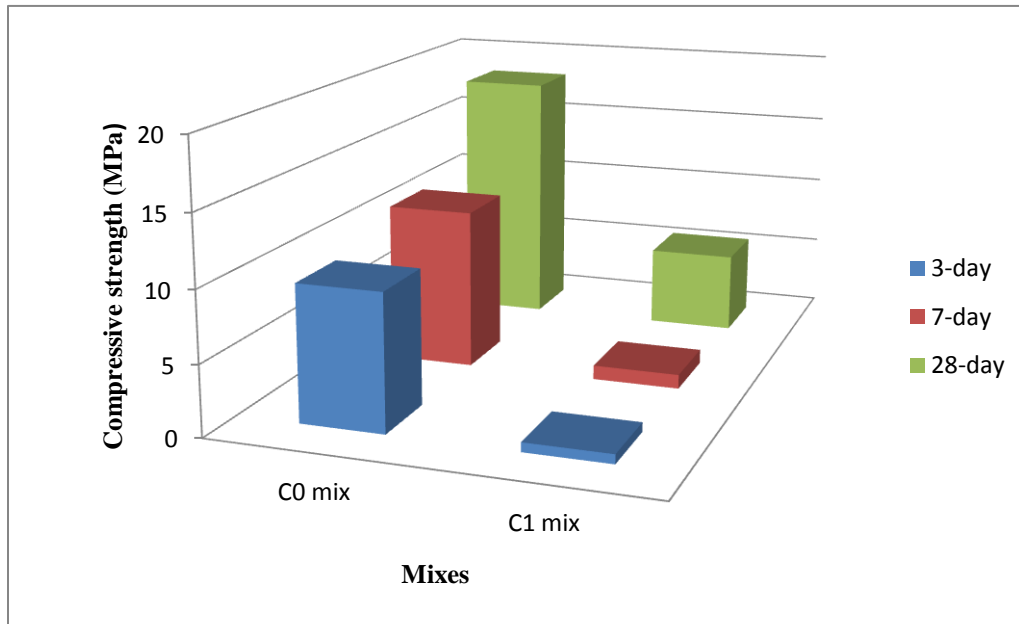


Figure 4.3 – Strength development for mix C0 and C1

4.1.3 CONCLUSION

The purpose of this project was to optimise the material quantities of the CLSM to achieve sufficient flowability, consistency and compressive strength.

The pour was conducted to understand problems associated with mixes of high water/cement ratio with no filler materials and yet to attain the desired compressive strength of 1 MPa at day 7. The following statements have been concluded based on the results from this study.

The unmixed free water and unacceptable segregation caused due to the high water content will require some inert material which could absorb water and still not enhance the compressive strength of the mix. The addition of Pulverised fly ash or limestone dust could increase the workability and consistency of the mix. From the results of the mix C1, it maybe concluded that the necessary quantity of

cement in a CLSM mix should be less than 100 kg/m^3 . To reduce the cement content and early age strength, a supplementary cementitious material such as GGBS could be used as a replacement.

4.2 BASIC CEMENT AND GGBS BINDER MIX

4.2.1 PREVIOUS WORK

GGBS is a cementitious material that can act as a cement replacement in concrete. Last year a Master's student Darragh O' Rourke carried out a series of tests for cement/GGBS CLSM mixes. The testing was carried out in Trinity's laboratory. It was hoped that the GGBS, which may not be as fine as the cement or PFA, and is quite variable in nature, would be able to provide sufficient consistency.

O'Rourke began with 90 kg/m^3 of GGBS, which replaced cement content in the region of 60- 90%. The presence of GGBS was found to provide lesser consistency and flowability of the mixes. The water/cement ratio was reduced as the fine content in the mix was not enough to absorb the water. O'Rourke increased the fines content in the mix and used a new mixing procedure (i.e. first adding $\frac{1}{2}$ water to the mix and the second half of the water content was added in eighth's ($\frac{1}{8}$), where the mix would be poured out to be observed in a flow table test at each stage). A highly flowable and consistent state was observed, but the relatively low water/cement ratio showed that the target strength of 2MPa at 28 days was exceeded. Based on the new testing procedure, it meant that a highly flowable and consistent GGBS/cement CLSM mix can be potentially obtained for low strength structural purposes but cannot be used for this project as the compressive strength for 7-day is more than 1MPa.

O'Rourke detailed summary of his pours is given by table 4.3, and shows that at high water/cement ratio the compressive strength of 1MPa at 7-day can be achieved but the mixes fail in satisfying the fresh state properties of a typical CLSM mix. In this project, a cement/GGBS mix was to be carried out to understand

the problems to be rectified by deriving the ternary mixes is incorporating filler materials with cement/GGBS mix.

Table 4.3 O'Rourke mix proportions of mix G0, H0, I0 (O'ROURKE, 2012)

Mix I.D	Cement (kg/m ³)	GGBS (kg/m ³)	Water (l/m ³)	Water/cement ratio	7 day (MPa)	28 day (MPa)
G0	60	100	305	1.91	1.01	2.97
					1.21	2.81
H0	20	140	300	1.88	0.79	1.62
					0.83	1.68
I0	50	150	300	1.50	1.72	4.13
					1.55	3.98

4.2.2 INTRODUCTION

Based on previous work carried out on cement/ GGBS CLSM mixes, it is clear that with a low cement/fines ratio, the workability of the mix is somewhat attained but the objective of compressive strength being less than 1 MPa at 7 days could not be achieved. In this project, the main focus is to make GGBS work by incorporating other filler materials into the mix.

The pours were derived and carried out on February 18th. As understood from the previous work, the mix is designed to have a high water/fines ratio so that compressive strength is within the permissible limits for this project. The idea behind this pour is to understand the workability issues related with a GGBS mix, so that they could be rectified using filler materials in the later chapters. The initial mix quantities which were derived can be seen in the table below (table 4.4):

Table 4.4 - Mix proportion for mix G00

Mix ID	Cement (kg/m ³)	GGBS (kg/m ³)	Water (l/m ³)	Sand (kg/m ³)	W/fines ratio
G00	50	150	320	1650	1.6

4.2.3 FRESH STATE OBSERVATIONS (G00)

From the first pour carried out, it was clear that there was too much water present in the mix. The absence of a workability agent was clearly evident. It could be immediately seen that the water reducing capacity of a workability agent was missed as the excess water caused the sand to segregate to the bottom of the mixing drum. As the water/fines ratio was kept high, the fines content in the mix was not enough to absorb the water. Mix G00, which comprised of a 75% GGBS cement replacement content, experienced consistency problems, the GGBS and sand did not mix well, a lot of segregation and bleeding occurred, pools of unmixed water formed as shown in plate 4.2.



Plate 4.2 - Pools of water formed in mix G00

The flow diameter from the flow table test was measured to be 590mm which is just below the target range of flows; however the water in the mix had not fully been absorbed into the mix meaning there was a lack of fines. The cross section of the material is shown in plate 4.3, in which one can see that the water has risen to the top of the material leaving behind a dry sandy surface below.

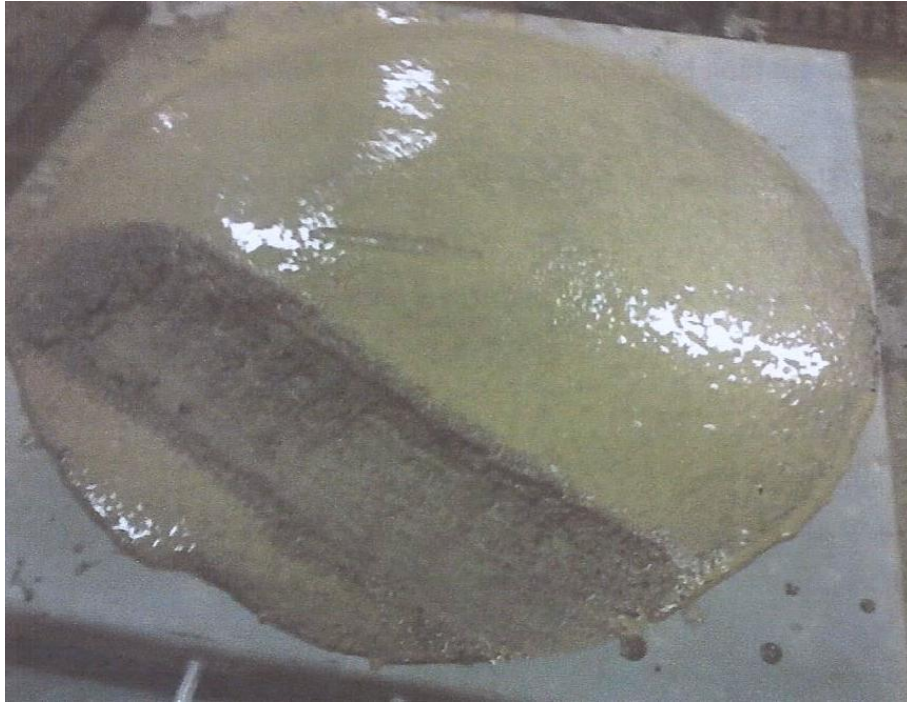


Plate 4.3 – Cross section of material

4.2.4 HARDENED STATE (G00)

On demoulding of the cube, it could be seen that there was a significant difference in the surface texture between the cement cube and cement/GGBS cube. The cement cube, which had shown excellent consistency, had a smooth and uniform surface; however the cement/GGBS surface was rough, sandy and appeared to be non-uniform. From observing the cube specimen, it emerged that the cement/GGBS grains had clumped together. This was made clear as the finer GGBS particles are a white colour whereas the courser sand has a darker appearance.

This observation that the materials are clumped together proves that the mix is inconsistent and, therefore, not adequate.

As the water/cement ratio was kept high, it was expected that the 7-day and 28-day cube strengths of mix G0 would be in the range of the target strength.

Table 4.5 Compressive strength for the mix G00

Mix I.D.	Cement (kg/m ³)	GGBS (kg/m ³)	Water (l/m ³)	Water/Cement ratio	3-day (MPa)	7-day (MPa)	28-day (MPa)
G00	50	150	320	1.6	0.35	0.97	2.21
					0.32	1.17	2.10

For this mix the cube strength had in fact exceeded the target as seen in table 4.5. The 28-day strength which is marginally over 2MPa means that the material may be the strong for it to be excavated at a later date using conventional digging equipment. Due to the inconsistent nature of the pour, one can also see a slight variation on the cube strength at 7-days where there is approximately a 20% difference in cube strength, which is normally only supposed to be 15%. The cubes developed only approximately 40% of their 28-day strength at 7 days. This slower strength gain is expected and could be explained by the presence of GGBS in the mix. When GGBS is added to the mix, it slows down the rate of hydration which implies that the early age strength of the material will be lower compared to the mix consisting Portland cement only.

It must be also noted that the ultimate compressive strength of GGBS concretes are higher due to the higher proportion of Calcium-Silicate-Hydrate (C-S-H) present, which is the gel that binds the aggregates together and provides material with its strength. The GGBS consumes the weak Calcium Hydroxide (CH) over time and replaces it with the more stable C-S-H gel. Also, it is not uncommon for

GGBS concrete to increase its 28-day compressive strength by a further 20% at 90 days (Ecocem, 2012).

4.2.5 CONCLUSION

The cement/GGBS CLSM mix did not satisfy the fresh state properties as it segregated, was inconsistent and a lot of unmixed water was present in the mix. To rectify this problem, a ternary mix incorporating other fines such as PFA and limestone dust, will have to be derived, as the fines present in the mix was not enough to absorb all the water present in the mix.

CHAPTER 5 - TERNARY MIXES

From previous chapters it has been seen that cement, cement/GGBS mixes do not comply with the properties CSLM required for this project. To rectify this, ternary CLSM mixes will be derived using limestone dust and fly ash in addition to GGBS to improve the consistency, workability and still suppress the 7-day compressive strength below 1MPa. An aim is to optimise the mixture ratios for performance using trial mixes which use various combination of these cementitious and filler materials.

5.1 TERNARY CEMENT, GGBS AND FLY ASH BINDER MIX

5.1.1 INTRODUCTION

Pulverised fly ash (PFA) is a by-product of the combustion of pulverized coal in electric power generation plants. When the pulverized coal is ignited in the combustion chamber, the carbon and volatile materials are burned off. However, some of the mineral impurities of clay, shale, feldspars, etc., are fused in suspension and carried out of the combustion chamber in the exhaust gases. As the exhaust gases cool, the fused materials solidify into spherical glassy particles called Fly Ash. The use of this pozzolan (i.e. it acts as a cementitious material in the presence of lime) in CLSM leads to economic and environmental benefits. These benefits include recycling a waste product, which would otherwise be dumped in the environment, reducing the cement content in the CLSM which reduces cost and also the presence of PFA in CLSM has shown to improve the flowability of the material as well as reduce the effects of bleeding. The spherical shape of the particles in the PFA, which acts as ball bearings, provide a more workable material, which means the water content can be reduced. Subsequently this will mean a reduction in cement content in order to acquire the required water/cement ratio. This reduction of cement reduces the cost of the mix. Therefore the replacement of Portland cement by this waste material may also

reduce the cost of construction as well as conserving energy and natural resources.

As the cement reacts with water in the mix, the hydration products which are most abundant are Calcium Silicate Hydrate (CSH) and Calcium Hydroxide (CH). The pozzolan reacts with this CH to form additional CSH gel over time; this is known as secondary CSH which is formed from the pozzolanic reaction. CSH is the product that binds the aggregate together and provides material with its strength. On hydration of the cement, the CSH gel comprises of approximately 65% of the total volume of cement paste whereas CH accounts for approx 15% of the volume. The presence of this pozzolan in the mix acts as a retarder and reduces the rate of heat of hydration, meaning the early age strength of the material will be suppressed. However, as the pozzolan consumes the CH over time it is expected to increase the long term strength of the CLSM.

As mentioned previously the CH, which reacts with PFA to form a cementitious material, only accounts for about 15% of the cement paste. This means that there is not CH present for all the PFA to react with if high PFA quantities are used. Essentially, PFA has a secondary role in that it also acts as filler. The PFA which does not react with the CH is fundamentally inert, but this is an advantage for the CLSM mixes as the fine well rounded particles provide a consistent and flowable mix.

In this ternary mix, PFA will more contribute to the consistency of the mix than the compressive strength at an early age as PFA has finer particles as compared to GGBS and the less CH present (i.e. cement content would be less to attain the required compressive strength) to react with PFA. There had been no previous trial mixing carried out on these mixes, so it was not known how they would perform. The initial mix quantities were derived as can be seen in the table below (table 5.1).

Table 5.1 Mix proportions for mix F0, F1

Mix ID	Cement (kg/m ³)	GGBS (kg/m ³)	PFA (kg/m ³)	Sand (kg/m ³)	Water (l/m ³)	w/c ratio
F0	30	270	180	1440	320	0.60
F1	25	190	150	1575	300	0.83

5.1.2 FRESH STATE OBSERVATION (F0, F1)

From the first pour (F0) that was conducted, the mix was very consistent and cohesive due to the high amount of fines present in the mix. The PFA contributed to the consistency of the mix by improving the particle packing. It was obvious that PFA would assist in rectifying the fresh state properties of the cement/GGBS mix. The mix was highly cohesive and sticky in nature, due to the low water/fines ratio. The reduction in water demand was due to well rounded PFA particles which provided flowability. From the flow test, a flow diameter of 680 mm was measured which is within the range of the target flows. The high fines amount present in the mix though improved the flowability but the mix was less workable as it was very cohesive and sticky as shown in plate 5.1. The fresh density of the

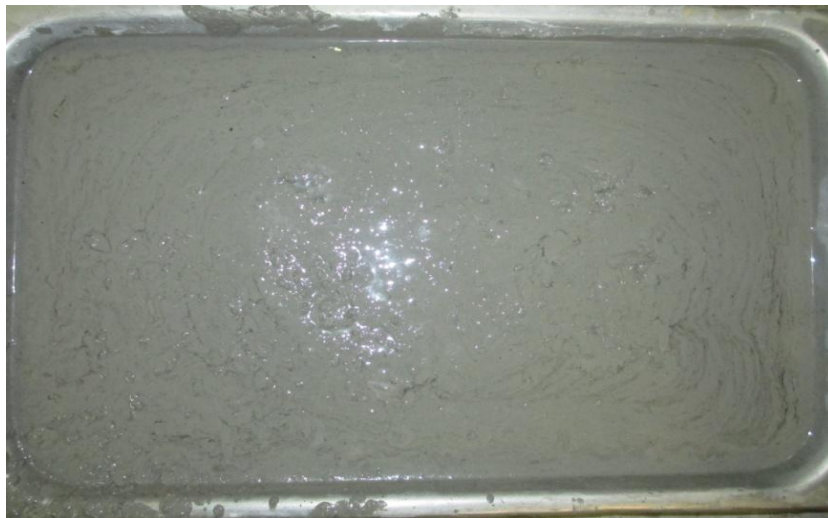


Plate 5.1 - Highly cohesive mix (F0)

mix was measured to be 2240 kg/m^3 . The water was completely mixed in the mix as the result of no segregation occurring.

Mix F0 was very dense and had high packing density which might ultimately increase the compressive strength outside the required range for this project. The next mix F1 was derived on the idea of lowering the fines content in the mix. For the mix F1, the GGBS content was lowered to 190 kg/m^3 from 270 kg/m^3 and PFA was lowered by 30 kg/m^3 . The fines content was reduced in the mix; thereby the water/fines ratio was increased to 0.83 from 0.60. The cement content was slightly reduced therefore a lesser amount of CH was produced that the PFA can react with. This will mean that the majority of the PFA is acting as filler in the mix and is predominantly present to achieve the required consistency and flow. The lowering of fines helped in obtaining a cohesive and non-sticky mix unlike F0. The flowability of mix F1 was observed to be excellent. From the flow table test, a flow diameter of 670mm was measured. Plate 5.2 and 5.3 show the material after the cone has been lifted and after the flow test had been carried out.



Plate 5.2 - Cone lifted for flow test (F1)

Light bleeding was observed on the cubes immediately after they were cast which is reasonable as high fines means slow the setting time for the CLSM mixes. The mix constituents of the next three pours are shown later in table 5.3.



Plate 5.3 – 670mm flow diameter of mix F1

5.1.3 HARDENED STATE (F0, F1)

Similar to all previous pours, eight cubes were cast after pouring, two each being tested at 3, 7, 28 and 56-days. The cubes when struck out after 48 hour had a smooth surface as lot of filler material was present in the mix. The compressive strengths of the mixes are shown in table 5.2.

As seen the strengths of these mixes are in excess of the required strength for this project. The cement content (30 kg/m^3 , 25 kg/m^3) in the mixes F0 and F1 respectively is quite the same as compared to the GGBS and PFA content. In these

Table 5.2 Compressive strength for the mix F0, F1

Mix ID	w/c ratio	3-day (MPa)	7-day (MPa)	28-day (MPa)
F0	0.60	2.10	4.92	8.34
		2.21	5.10	8.28
F1	0.83	1.07	4.15	7.86
		1.15	4.30	7.74

mixes, calcium hydroxide (CH) is released when Portland cement reacts with water serves to activate GGBS, it does not help in early age strength as for GGBS the rate of reaction is slow. Hence, for mixes F0, F1 the 3-day strength should be low but as seen in table 5.2, the low water/fines ratio and high fines content enhances the compressive strength for the particular age. As the fines content is lowered for F1, the 3-day strength comes down to 1.1MPa which would be still above the target range of less than 1MPa at 7-day. The increase in compressive strength for 7-day F0 and F1 is quite high, as the GGBS and PFA starts contributing to strength. The GGBS reacts with water in the same way as the Portland cement but needs an activator CH, which is formed during hydration of the cement. Once the GGBS starts hydrating and forms C-S-H gel the additional CH which now reacts with the PFA to form secondary C-S-H gel. This process explains the high compressive strength increase at 28-day and 56-day.

The fines content was lowered for F1 which thereby shows the reduction in compressive strength when compared to mix F0. The averaged cube strength for the F1 mix at 28-day is 7.8MPa which means that mixes have gained approximately 55% of their compressive strength after 7-day. Both F0 and F1 mixes have compressive strengths which are quite high for the desired motive of this project. As a result, mixes F0 and F1 are considered inadequate for this project though they satisfy the fresh state properties of a typical CLSM mix.

Table 5.3 Mix Proportions of mix F2, F3, F4

Mix ID	Cement (kg/m ³)	GGBS (kg/m ³)	PFA (kg/m ³)	Sand (kg/m ³)	Water (l/m ³)	w/c ratio
F2	25	170	100	1620	300	1.02
F3	15	150	70	1680	320	1.36
F4	15	160	50	1680	330	1.50

5.1.4 FRESH STATE OBSERVATION (F2, F3, F4)

From mix F2, a consistent and flowable mix was observed. The GGBS content had been reduced from 190 kg/m³ to 170 kg/m³ with the PFA content decreased by 50 kg/m³ to achieve an adequate water/fines ratio. The water content of the mix was gradually added until a consistent/flowable state was observed in the drum. At this stage no more water would be added to the mix. The flowability of the mix was observed to be excellent, the flow table test confirmed this and produced a diameter of 700mm, this value is within the range of the target flow. As the fines content was reduced, the mix had adequate cohesiveness due to which it had high flowability. It is hoped that with the increased water/binder ratio and reduced fines content, this would provide a material with a lower strength than that of mix F1, which had a approximate 7-day strength of 4.20MPa.

For the next two pours F3 and F4, the idea was to decrease the fines content and still design a CLSM mix which is consistent and workable so that it complies with the fresh state properties of a typical CLSM mix. As seen from the previous mix, the low water/fines ratio resulted in a higher compressive strength than the required range of target strength.

For the mix F3, the cement and PFA content both were reduced with sand content in the mix increasing. Reducing the cement content will mean a reduction in the Calcium Hydroxide (CH) produced during hydration. This means there is less CH for the GGBS and PFA to consume in order to act as a cementitious material. It

was hoped that this step would reduce the compressive strength. Similar to the mix F2, the water quantity was poured into the mix in portions, once the consistency and flowability was observed to be cohesive and adequate, adding water ceased. The flow table test produced a sufficient flow diameter of 650mm. As the fines content was reduced, moderate bleeding would be observed on the cubes after casting which is seen in the plate 5.4. Overall, the mix was adequate in terms of the fresh state properties of the CLSM mix.

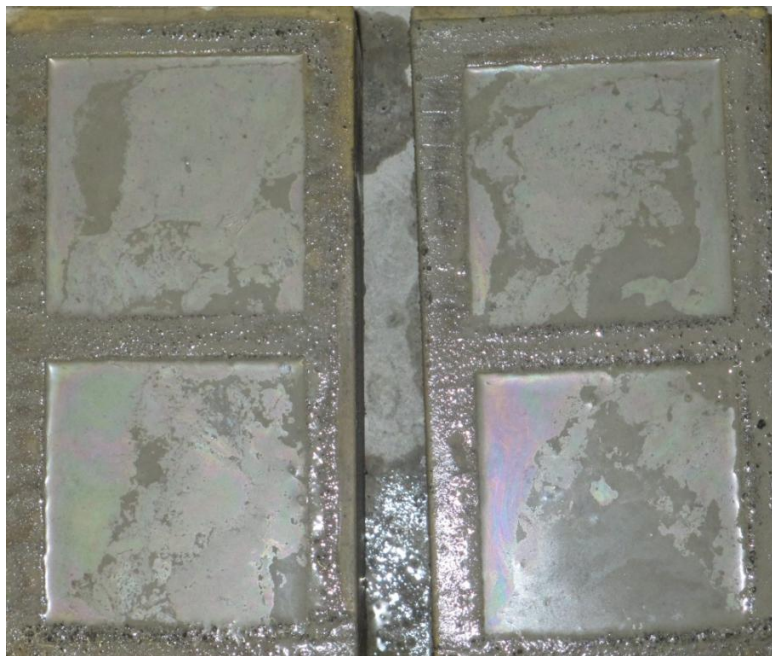


Plate 5.4 – Bleed water when casted (F3)

For the next mix F4, the objective was the same as for mix F3. The water/fines ratio was increased by reducing the fines content. The water/fines ratio was increased from 1.36 to 1.50 and the water content was increased by 25 kg/m³. The mix was still consistent but some pools of unmixed water were formed when the mix was kept untouched in the mixing drum for a while, as shown in plate 5.5. When the mix was again mixed in the mixing drum, the water would again mix uniformly into the material. As the fines content was reduced, the flow table test



Plate 5.5 – Pools of water in the mixing drum (F4)

diameter for this mix reduced to 620mm as compared to previous mixes, which is still in the range of the target flow. Plates 5.6 and 5.7 shows the material after the cone is lifted and after the flow table test is carried out.

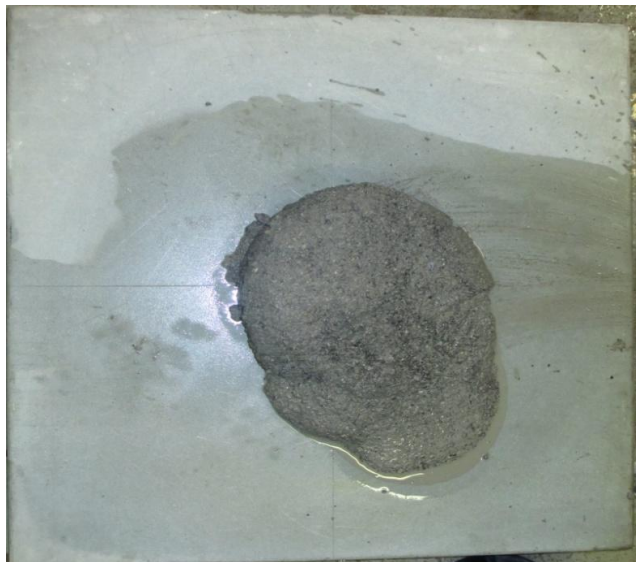


Plate 5.6 – Cone lifted for mix F4

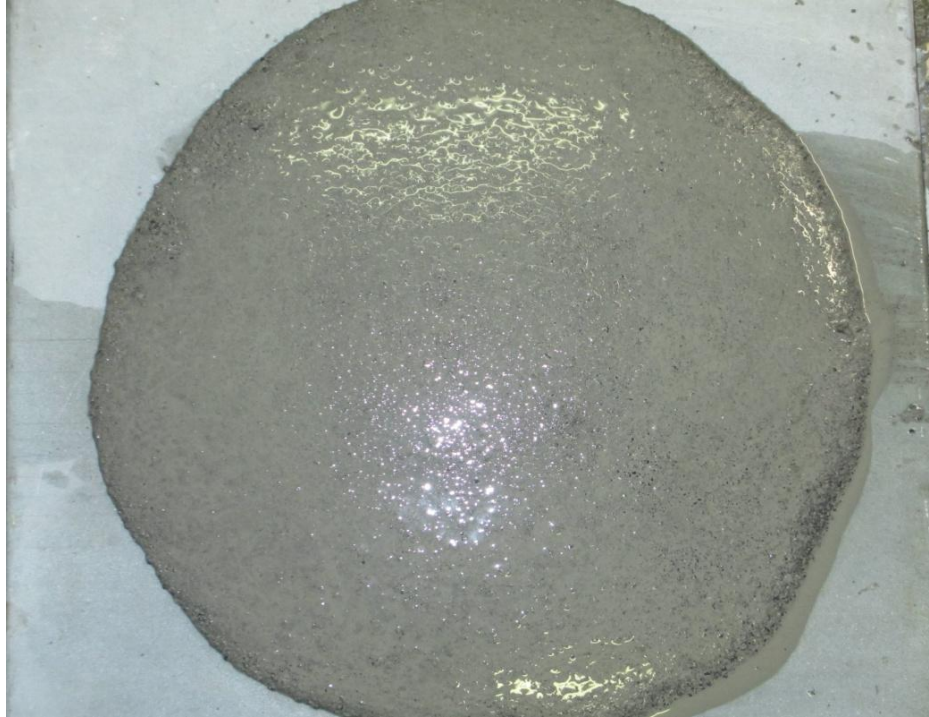


Plate 5.7 - Flow table test (F4)

As seen in the plate 5.7, there is a thin layer of water over the material after the flow table test is carried out, which shows the mix has segregated slightly.

5.1.5 HARDENED STATE (F2, F3 AND F4)

On demoulding of the cubes it could be seen that the cubes had self compacted, This was expected due to the high flowability of the mixes. The compressive strength of previous (F0 and F1) mixes were way more than the desired strength required for this project, as they had low water/fines ratio and high amount of fines present in the mix, which has been lowered for the present F2, F3 and F4 mixes. The compressive strength for the mixes for 3, 7, 28 and 56-day is shown in table 5.4.

Table 5.4 Compressive strength for mix F2, F3, F4

Mix ID	w/c ratio	3-day (MPa)	7-day (MPa)	28-day (MPa)
F2	1.02	0.75	3.89	5.85
		0.80	3.99	5.92
F3	1.36	0.43	1.78	4.09
		0.39	1.72	4.12
F4	1.45	0.72	1.61	4.39
		0.71	1.59	4.51

From table 5.4, it can be seen that for mix F2 the compressive strength at 3-days is much less than 1MPa but at 7-day there is a high rise in strength, mainly due to GGBS and PFA present in the mix, which have a slow rate of reaction and starts reacting with the CH produced during the hydration of cement. The cement content was very low in this mix but GGBS only requires a small amount of CH as a activator for its hydration. Another reason for this increase in strength is the presence of a volume of PFA which has tiny spherical particles that improves the particle packing of the mix. The 7 and 28 days strengths of the mix F2, is above the required target strength. Thus, the mix F2 is inadequate for this project.

For the next mix F3, the PFA content was lowered from 170 kg/m³ to 70 kg/m³ and cement content was reduced by 5 kg/m³ when compared to mix F2. It was hoped that reducing of the fines and cement content would help in lowering the compressive strength to the desired level. As seen before, the 3-day strength was very low for this mix. For this mix, the averaged 7-day strength was 1.7MPa, which is still above the desired 1MPa strength. It can be seen by reducing the PFA content by 100 kg/m³, the strength lowers to 1.7MPa from 3.85MPa when compared to the mix F2. From the above statement, it could be understood that the PFA mainly contributes to the 7-day strength as the GGBS content was not varied much in the vast proportions for these mixes. The 28-day strength of the

F3 mix, was above the desired strength for this project as the GGBS contributes to the long-term strength as discussed earlier in this chapter. As the 28-day was way above the desired strength, so the 56-day strength was expected to be more, so it was not measured as it is out of the context of this project.

For the mix F4, the compressive strength followed the same trend as for the mix F3. The GGBS content was increased by 20 kg/m³ and PFA was lowered by 20 kg/m³. As seen before there was a slight decrease in the 7-day strength as the PFA content was lowered and a slight increase in the 28-day strength as the GGBS content was increased.

5.2 TERNARY CEMENT, GGBS AND LIMESTONE DUST BINDER MIX

5.2.1 INTRODUCTION

Cement manufacture produces a large amount of undesirable products, mostly CO₂ which results in a greenhouse effect that leads to the earth's temperature increase. In addition, the cement production process is energy intensive as well as raw material demanding. Technical developments to lower the environmental impact of cement production are achieved by the reduction of cement demand using blended cements. Therefore, many studies have given considerable attention to mineral additions such as slag, natural pozzolana, fly ash and limestone in order to reduce energy consumption and CO₂ emission. Nowadays limestone has been widely used to add and replace a part of Portland cement to produce Portland limestone cement and Portland composite cement.

The limestone is calcareous sedimentary rock mainly consisting of calcium carbonate (CaCO₃), commonly called calcite. Limestone is used in cement and concrete for various purposes, namely as a raw material for clinker production and as a coarse or fine aggregate. Limestone powder is used by grinding limestone in quarrying operations and has been suggested for use as an additive in Portland cement. Replacing of limestone in Portland cement has been widely studied for several years. Limestone is usually considered as an inert filler material that marginally improves the hydration rate of cement compounds and consequently increases the strength at early ages. The incorporation of limestone powder with Portland cement improves strength, durability and workability. While some authors claim that limestone acts as an active participant and that during the hydration of Portland cement some calcium carbonate is taken into the system and reacts with the alumina phases of cement to form carboaluminates and delays and impedes the ettringite-monosulphate transformation. This leads to the stabilization of the ettringite and will result in an increase in the total volume of hydration products, which might result in a decrease in porosity and

thus an increase in strength. The effect of this chemical interaction in PC-limestone system is however, not so pronounced due to limited aluminates content in the clinker.

Due to the fineness of limestone dust, the water absorbing capacity of the material may be relatively high meaning the water demand for the mixes would increase to achieve sufficient flowability. However, as no previous testing has been carried out on cement/ limestone dust pours, it is not known how the material will behave.

Essentially, the limestone dust will have the same function as a workability agent. The material will increase the fines content and absorb the water leading to a stable, cohesive and flowable mix. As PFA and limestone dust are different materials with different properties it was not known if the water/fines ratio would be applicable to these mixes. With this in mind the following three trial mixes were derived and tested, where the mix quantities are shown in table 5.5.

Table 5.5 Mix proportions of mix L0, L1, L2

Mix ID	Cement (kg/m ³)	GGBS (kg/m ³)	LP (kg/m ³)	Sand (kg/m ³)	Water (l/m ³)	w/c	w/fines
L0	35	180	240	1560	270	1.25	0.59
L1	35	180	180	1540	310	1.54	1.02
L2	25	150	125	1620	300	1.70	1.00

5.2.2 Fresh State Observation (L0, L1, L2)

The mixing procedure for these trial mixes followed the same procedure of the cement/GGBS/ PFA pours in that the water cement was added in the portions until it appeared that the material had achieved a flowable and consistent state in the mixing drum.

Mix L0 began with a high fines content of 180 kg/m³ of GGBS and 240 kg/m³ of limestone dust. This mix was observed to be stable and consistent with a water/fines ratio of 0.59. The flow table test was carried out where a flow diameter of 620 mm was measured which is in the range of the target flow (600-700mm). The mix was very cohesive and sticky in nature, as the fines content was very high with a low water/fines. The fine particle of limestone dust increases the water absorbing capacity and increasing the cohesiveness as shown in the plate 5.8.



Plate 5.8 - Cohesiveness of L0 mix

As mix L0 achieved the required consistency, the mix will be slightly modified later in order to achieve high water/fines ratio and still maintain the flowability of the mix.

For mix L1, the limestone content was reduced by 60 kg/ m³. The water content of the mix which was initially derived to be 270 kg/m³ was increased by 40 kg/m³ during the mixing procedure. After the mixing procedure had finished, the material was observed to have a consistent and highly flowable state. The water/fines ratio has increased to 1.02, by the addition of extra water for this mix. The flow table test confirmed this where a flow of 640 mm was measured.

Although the mix has provided the required consistency and flowability, the low/water cement ratio may produce a high compressive strength. As seen for the ternary PFA mixes, the low water/fines ratio shows high early age strength due to the improved packing of the material.

Again, in order to optimize the characteristics and cost of the CLSM, the cement content, which is the most expensive constituent in the mix, was reduced down to 25 kg/m³. It is hoped that low cement content would help in getting the compressive strength in the target range. Mix L2 consisted of reduced cement GGBS and limestone content. Similar to mix L1, the water content originally derived at 270 kg/m³, was increased by a further 30 kg/m³ during the mixing process as the mix was deemed not to have the required flowability. After additional of extra water content the mix was observed to be consistent and highly flowable. The flow diameter measured was 650 mm. The water was completely mixed in the mix, and as a result no segregation had occurred.

In the above mixes, the ternary mixes incorporating limestone dust tend to rectify the fresh state properties of the cement/GGBS mix. The fine particles of the limestone dust improves the consistency and workability and reducing the segregation of mixes. It would be interesting to see how the inert material limestone dust contributes to the compressive strength of the CLSM mixes. Overall the above mixes were adequate in terms of the fresh state properties of CLSM mix. The next three pours will look to modify these pours by increasing the water/fines ratio and reducing the cement content and still achieve the consistency and flowability required.

Very moderate bleeding was observed on all three mixes. All mixes also underwent a slump collapse during the flow test as seen in plate 5.9. The consistency of mix L1 and the flow of mix L0 can also be seen in plates 5.10 and 5.11.



Plate 5.9 - Slump collapse mix L0



Plate 5.10 - Consistency of mix L1

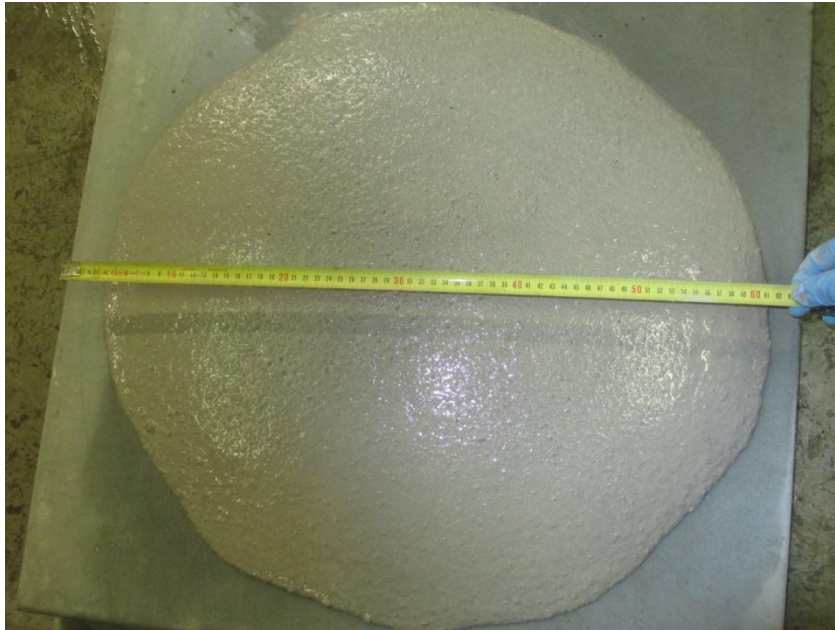


Plate 5.11 - Flow table diameter of L0

5.2.3 HARDENED STATE (L0, L1, L2)

Similar to all previous pours, eight cubes were cast after pouring, two each being tested at 3,7,28 and 56 day compressive strength. The compressive strengths of the mixes are shown in table 5.6.

Table 5.6 Compressive strength of mixes (L0, L1, L2)

Mix ID	W/C	W/F	3-day (MPa)	7-day (MPa)	28-day (MPa)
L0	1.25	0.59	1.48	5.84	9.8
			1.65	5.73	9.69
L1	1.54	1.02	1.17	4.15	7.4
			1.14	4.30	7.36
L2	1.7	1.00	1.02	3.87	6.6
			0.98	3.82	6.71

Mixes L0, L1 and L2 were the first cement/GGBS/limestone dust pours to be carried out. The focus of this project is to optimize the cement/ GGBS CLSM mixes by incorporating filler material to rectify the fresh and hardened properties required for this project.

The addition of a high content of limestone dust, which was considered as fundamentally an inert material, should not significantly contribute to the strength but for high volumes of limestone dust, the filling effect enhances the strength as the small particle size can fill the pores between cement and GGBS particles in the paste. Thus, the fineness of limestone powder used has an influence on the observed compressive strength values. Furthermore, it is known that limestone can provide nucleation sites for cement hydration and thus can, in small dosages, enhance early age but not long-term strength.

For mix L0, a high content of limestone dust of 240 kg/m^3 and GGBS of 180 kg/m^3 is used. Due to the high fine content, the packing density of mix was significantly enhanced. The 3 day strength of mix L0 was measured to be over the target strength of 1 MPa at 7 day. When PFA was added to a cement/GGBS mix previously, the 3 day strength was less than 1MPa, as it had a slow rate of reaction but limestone dust adds to the 3 day strength as it accelerates the setting time of paste by filling the pours between cement and particles due to the formation of carboaluminates. The 7 day strength of these mixes rises sharply as the GGBS is activated by the calcium hydroxide (CH) formed during cement hydration.

For the mixes L1 and L2, the idea was to reduce the fines content and increase the water/cement ratio, that the compressive strength of the mix was reduced. These mixes followed the same trend as the mix L0. The strengths of the mixes were much higher than the target strength required for this project.

All three mixes performed well for the fresh state properties of CLSM mix but the hardened state properties required were not achieved. The idea for the next pour

is to increase the water/fine ratio and find the typical range in which both fresh and hardened properties are satisfied.

5.2.4 FRESH STATE OBSERVATIONS (L3, L4, L5, L6, L7)

From the previous mixes, it has been seen that the addition of limestone dust of more than 100 kg/m³ imparts higher early age strength which exceeds the target strength for this project. For the said mixes, the limestone dust content is being reduced from 100 kg/m³ to 45 kg/m³ and subsequently varying the cement and GGBS content. In the mix L3, the water/fines ratio is increased to 1.03 and cement content to 25 kg/m³. The water content of the mix was added gradually until a consistent/flowable state was observed in the drum. At this stage no more water would be added to the mix. The modified water content is shown in the table 5.7.

Table 5.7 Mix proportions for mix (L3, L4, L5, L6, L7)

Mix ID	Cement (kg/m ³)	GGBS (kg/m ³)	LP (kg/m ³)	Sand (kg/m ³)	Water (l/m ³)	w/c	w/fines
L3	25	150	100	1660	310	1.54	1.03
L4	20	160	80	1690	300	1.60	1.15
L5	15	200	50	1650	320	1.49	1.20
L6	15	160	90	1650	320	1.83	1.20
L7	15	130	45	1725	305	2.10	1.60

The flowability of mix observed to be excellent; the flow table test confirmed this and produced a diameter of 670mm. This value is within the range of the target flow. The mix was consistent and cohesive as seen in plate 5.12. The water was uniformly mixed in the paste proving that there are sufficient fines present to absorb all the water. When the mix was left untouched, a moderate amount of bleeding is observed.



Plate 5.12 - Cohesiveness of the mix L3

For the next mixes, the water/fines is increased, thereby the consistency of the mixes is lowered. The idea is to reduce the fines content to the minimum value at which the mixes are still consistent and flowable. For the next mix L4, the limestone dust content is lowered to 80 kg/m^3 and cement content to 20 kg/m^3 . This content of limestone dust was enough to improve the fresh state properties of cement/GGBS mix making it consistent and flowable. Pools of water were found in the mixing drum when left untouched to hydrate for 15 minutes and when re-mixed the water was fully absorbed into the mix as seen in the plate 5.13. The flow table test produced a sufficient flow diameter of 670mm. As the fines content was reduced, a moderate amount of bleeding could be observed on the cubes after casting. Overall, the mix was adequate in terms of fresh state properties of CLSM mix.

For the next mix L5, the water/fines ratio was 1.2 and the limestone dust content was reduced to 50 kg/m^3 and the cement content was lowered by 5 kg/m^3 . It was hoped the compressive strength would be in the target range by reducing the fines



Plate 5.13 - Unmixed water in mix L4

content which reduced the absorbing capacity of the mix. The water content of the mix was gradually added until a consistent/flowable state was observed in the drum. At this stage no more water would be added to the mix. After mixing the contents for 15 minutes in the drum mixer and then keeping it untouched caused the layer of water at the surface as seen in plate 5.14. The flowability of the mix was observed to be excellent again and the flow table test produced a diameter of 670mm which lies in the range of target flow. As the water/fines ratio was increased, there were not enough fines to absorb all the water. The unmixed water did mix, when the pour was remixed again. The mix was consistent and flowable as seen in plate 5.15. Bleeding was observed on the cubes immediately after they were cast which is reasonable as high water/fines ratio. For the next two pours L6 and L7, the idea was to design a CLSM mix which is consistent and workable so that it complies with the fresh state properties of a typical CLSM mix by decreasing the fines content to the maximum limit possible.



Plate 5.14 - Water on the surface in the drum mixer for mix L5

For the mix L6, the GGBS content was lowered to 160 kg/m^3 and the limestone content was increased to 90 kg/m^3 . The idea was to increase the believed inert material, which is limestone dust so as to improve the fresh state properties and decrease the GGBS content which would lower the 7-day compressive strength gain. The flow diameter was measured to be 670mm. The mix was less consistent when compared to mix L5. Lot of unmixed water was present when the mix was left untouched for 10 minutes so that the paste hydrates as seen in the plate 5.16.

For the mix L7, the cement content was kept same and limestone dust was reduced by 50% to a volume of 45 kg/m^3 when compared to L6. The sand content was raised by 125 kg/m^3 for the mix. As the fines content was lowered, the mix absorbed less water as it did for mix L6. After the pour was mixed in the drum mixer, the sand was observed to have settled as seen in the plate 5.17.



Plate 5.15 - Cross-section of material for mix L5

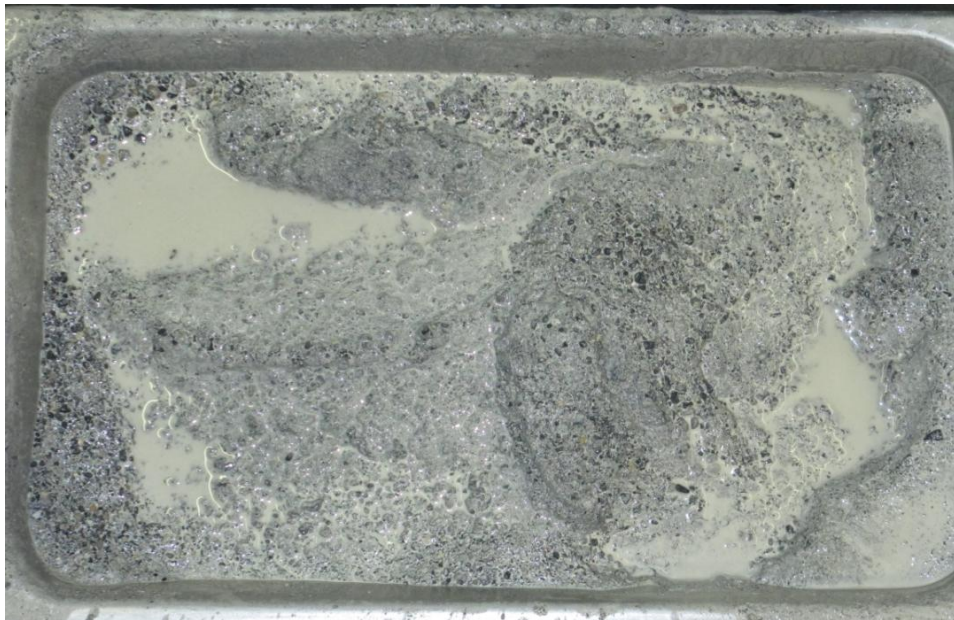


Plate 5.16 - Pool of water when mix kept untouched (L6)



Plate 5.17 – Sand settled in the drum mixer for mix L7

The limestone dust was 35% of the GGBS content, which seemed to be as the maximum replacement as beyond which the mix would fail in satisfying the fresh state properties. As the water/fines ratio was increased to 1.6 and fines content was lowered to maximum limit, it was expected that mix would attain the compressive strength in the required range which is 1MPa at 7-days.

The flowability of the mix was observed to be excellent; the flow table test confirmed this and produced a diameter of 690mm. This value is within the range of the target flow. The mix was slightly inconsistent and cohesive as seen in the plate 5.18. Heavy bleeding was noticed when the mix was left untouched, as not sufficient fines were present to absorb all the water.



Plate 5.18 – Slightly inconsistent but still cohesive mix of L7

5.2.5 HARDENED STATE (L3, L4, L5, L6, L7)

From the previous strength results of the mix (L0, L1, L2), it was seen that the high fines content enhanced the particle packing of the mix, thereby exceeding the allowed range of compressive strength limit. The idea for the above mixes was to increase the water/fines ratio till the maximum limit and still obtain a consistent and workable mix which satisfies the fresh state properties of a typical CLSM mix.

As for all previous mixes, 8 cubes were casted for each mix which was tested for 3, 7, 28 and 56-day strength. The cubes were struck out after 48hours and then were kept in the curing tank at 20°C. On demoulding of the cubes it could be seen that the cubes had self compacted. The compressive strength obtained the mixes for 3, 7, 28 and 56-day is shown in table 5.8.

Table 5.8 Compressive strength of mix (L3, L4, L5, L6, L7)

Mix ID	W/C ratio	W/Fines ratio	3-day (MPa)	7-day (MPa)	28-day (MPa)
L3	1.54	1.03	0.64	1.89	3.31
			0.61	1.93	3.28
L4	1.60	1.15	0.39	2.43	3.92
			0.42	2.33	4.00
L5	1.49	1.20	0.64	1.94	3.49
			0.64	1.86	3.92
L6	1.83	1.20	0.37	1.94	4.01
			0.67	1.83	3.92
L7	2.1	1.6	0.40	1.30	2.45
			0.41	1.07	2.59

From table 5.8, for mix L3 and L4 it can be seen that the 7-day strength is inching towards 2 MPa or more than 2 MPa, which is above the target strength for this project. The 3-day strength for all the above mixes is much less than 1 MPa but at 7-day there is a high rise in strength, mainly due to presence of GGBS and limestone dust in the mix. The GGBS has low rate of reaction as Calcium Hydroxide (CH) produced during cement hydration would activate the GGBS hydration. The limestone dust is fundamentally known as inert material and provides the filler effect in the mix. The fine particles of limestone dust do enhance the packing density of the mix, thereby increasing the early compressive strength.

For mixes L4 and L5, the 28-day is near to 4 MPa which was twice the strength as required for this project. The cement content used was 20 kg/m³, which is quite low that means that the GGBS behaves as a cementitious material. The strength

gain due to GGBS is slow but it does affect the long term strength. Whereas, the limestone dust used provide nucleation sites for cement hydration and thus can, in small dosages enhance early age strength but not the long term strength. As seen from the result strengths, the mix L3 and L4 do not comply with the hardened properties required for this project.

For the next two mixes, the idea was to increase the water/fines ratio and decrease the GGBS content, so as the strength of 7 and 28-day decrease to fall in the required range. But as the water/fines ratio was increased it was seen that the mix starts not to comply with the fresh state properties of a typical CLSM mix.

For mix L5, the cement content was lowered to 15 kg/m³ and the limestone content was taken to be 25% of the total GGBS content used. As the fines content was reduced, the GGBS added to more strength due to its cementitious properties. When the cube was tested for 3-day strength, it had a rough surface with voids visible on the surface of the cube as the limestone dust content was reduced as seen in plate 5.19.



Plate 5.19 - Rough surface and cracking pattern for mix L5

The cement/GGBS/limestone dust shows smaller 28-day compressive strength than cement/GGBS/PFA, as the fly ash adds to long-term strength whereas

limestone dust causes an increase of hydration at early ages inducing a high early strength, but it can reduce the later strength due to the dilution effect. On the other hand, GGBS contributes to hydration after seven days improving the strength at medium and later ages.

From table 5.8; the mixes L5 and L6 shows to have a compressive strength of 1.9 MPa at 7-day which is slightly above the desired 1 MPa strength. The mix L5, seemed hard to be consistent and workable as it had high water/fines ratio which thereby resulted in rough edges of the cubes that were tested for 7-day strength as seen in plate 5.20.

As seen from previous pours of water/fines ratio of 1.2 and less, resulted in 2 MPa or more strength at 7-day. For the next mix L7, the limestone dust content was reduced by 50% when compared to mix F5. The water/fines ratio was raised to 1.6 and it was seen that the mix did not perform well for the fresh state properties. The 7-day average strength was measured to be 1.1 MPa, which was acceptable for the requirement for this project. But the fresh properties needed to improve as free water was noticed on the surface when the mix was kept untouched.



Plate 5.20 - Rough edges of 7-day cube for mix F5

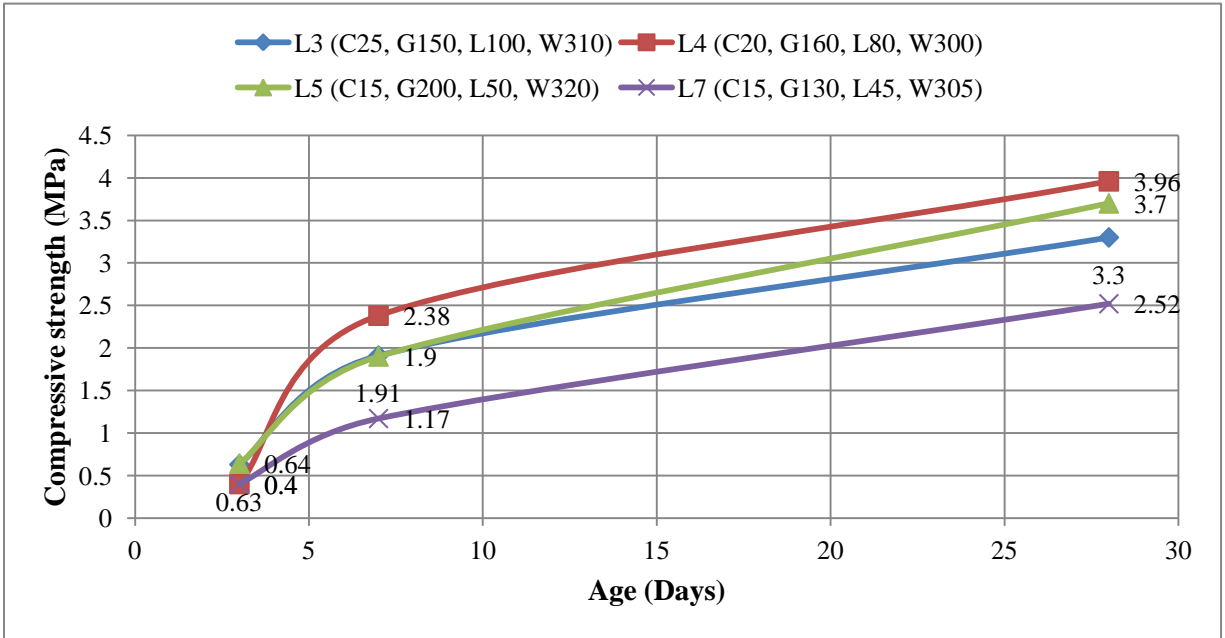


Figure 5.21 - Age versus compressive strength graph of mix L3, L4, L5, L7

From the graph in figure 5.21, it can be seen that mix L7 acquire the minimum strengths at 3, 7 and 28-day as the GGBS content and limestone content were decreased by keeping the same water content. The mix L3 and L5 have the same 3 and 7-day strengths but for 28-day strength, mix L5 shows higher strength than L3. Though the cement content was less in mix L5, the high GGBS content of L5 of 200 kg/m³ resulted in long-term strength as GGBS has slow rate of reaction. It can be stated that the water/fines ratio of 2.0 or more will result in compressive strengths which will satisfy the limit for this project.

5.3 CONCLUSION

5.3.1 BINARY TO TERNARY MIXES

In the chapter 4, the basic cement/GGBS mix G00 was seen to fail in fresh state properties as the mix segregated and lot of unmixed water was present. To rectify this, in chapter 5, ternary mixes were derived which were cement/GGBS/PFA and Cement/GGBS/limestone dust. The idea for the trail mixing was to start with high fines content and then to find the minimum fines content at which mix was satisfactory for both fresh and hardened state properties required for this project. When ternary mixes were poured by incorporating PFA and limestone dust to the basic mixes, they showed excellent workability and flowability seen in figure 5.1.

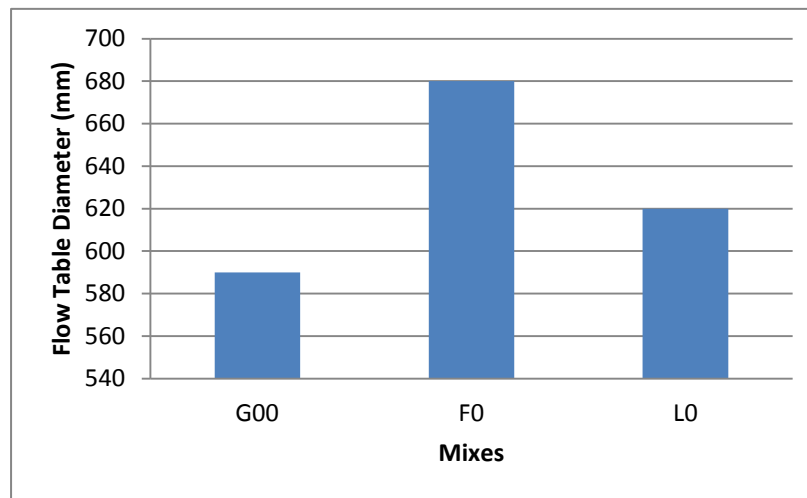


Figure 5.1 – Graph for Flow diameter of mixes (G00, F0, L0)

The mix F0 showed highest flow table diameter of 680mm which is more than mix L0 as the fly ash particles are well rounded and spherical shaped which tends to increase the flowability of the mix. Well, ternary mixes were satisfying the flow table diameter range of 600mm to 700mm for a typical CLSM mix. In figure 5.2, the graph for the strength development for basic cement/GGBS mix (G00),

cement/GGBS/PFA mix (F0) and cement/GGBS/limestone dust mix (L0) mix is shown.

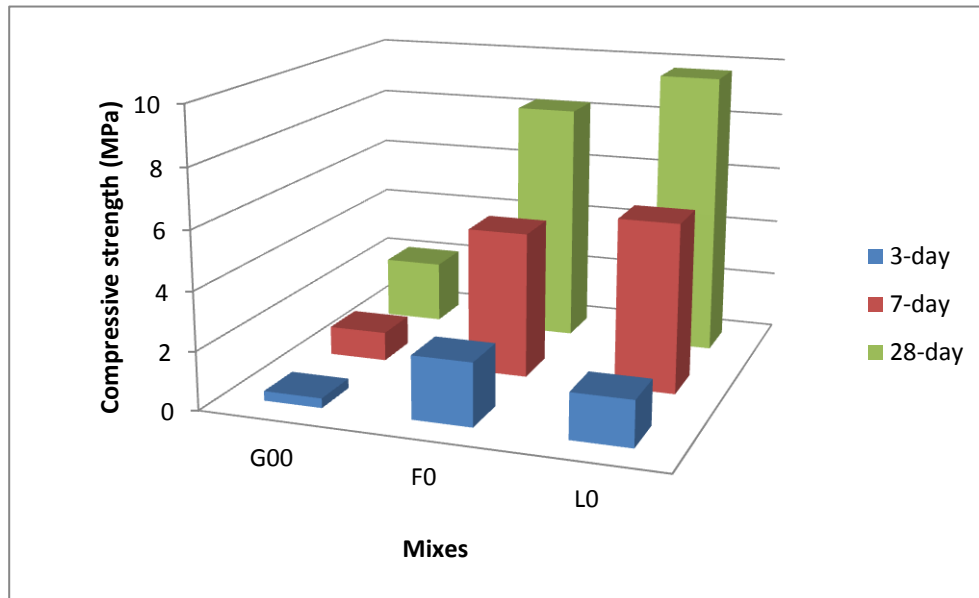


Figure 5.2 – Strength development for mixes (G00, F0, L0)

The L0 and F0 were high fines content mixes which were highly cohesive and sticky. It was clear that PFA and limestone dust imparted high flowability and tend to rectify the faults for basic cement/GGBS mix. The mix L0 had a very high limestone content which caused more 7 and 28-day strength when compared to F0 mix, as it improved the particle packing of the mix. The mixes F0 and L0 had high 7-day compressive strength which was way above the target strength of 1MPa required for this project.

The comparison for mixes G00, F3 and L6 are done for flowability and strength development. As all these mixes have the same GGBS content, which helps to understand how different filler materials added to basic G00 mix modifies the fresh and hardened properties. In figure 5.3, it can be seen that ternary mixes F3 and L6 tends to improve the flow table diameter when compared to G00. As mix L6 had high limestone dust content than fly ash in mix F3, it showed high flow table diameter.

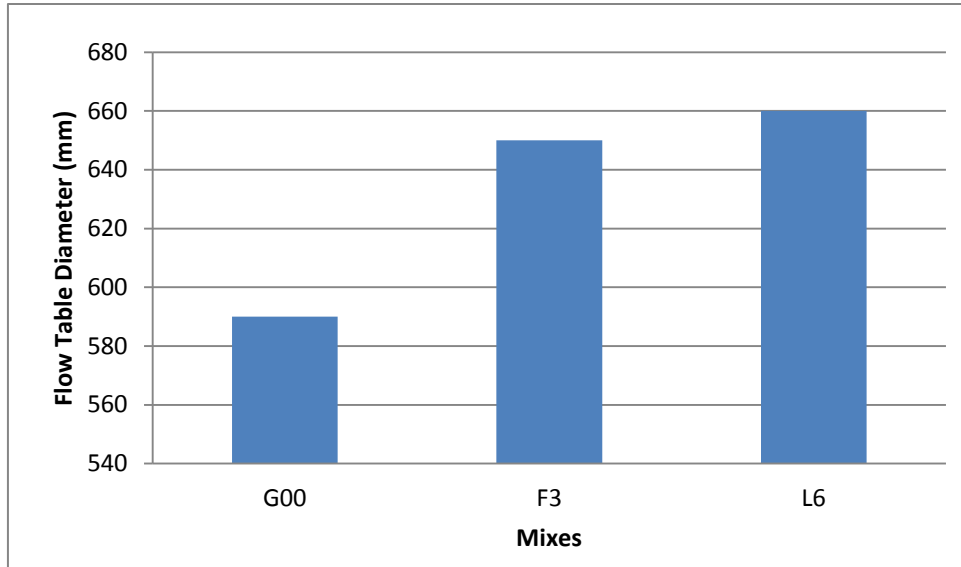


Figure 5.3 - Flow table diameter of mixes (G00, F3, L6)

In figure 5.4, the mixes G00, F3 and L6 strength development are shown. These mixes have the same GGBS content. The basic cement/GGBS mix G00, showed compressive strength of less than 1MPa at 7-day as the mix did not had any consistency and the cubes did broke from the edges.

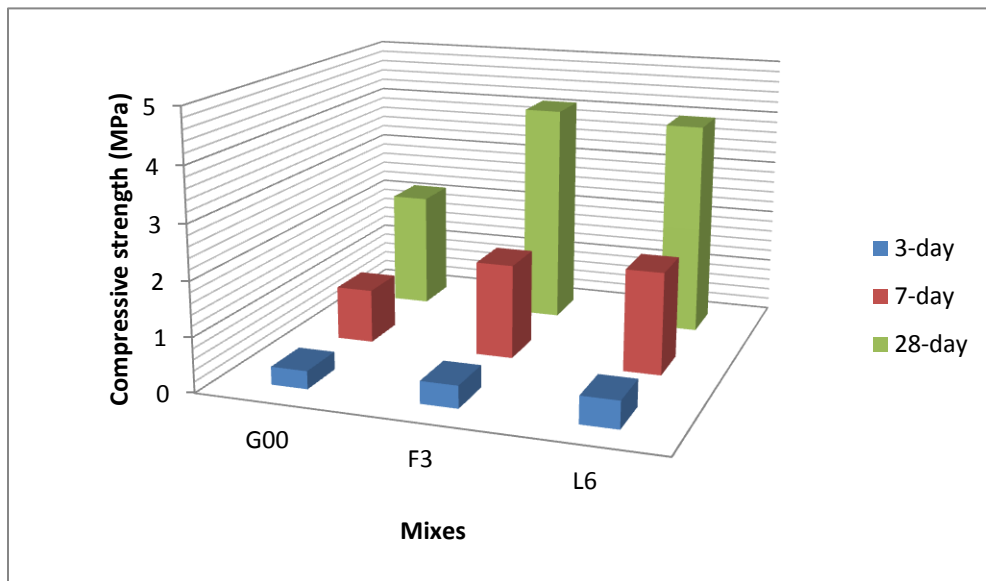


Figure 5.4 - Strength development graph for mixes (G00, F3, L6)

For ternary mixes F3 and L6, fly ash and limestone dust were added to basic cement/GGBS mix respectively to rectify the fresh state properties. It can be seen that the limestone content in the mix L6 caused high 3 and 7-day strength as it provides nucleation sites for cement and GGBS hydration which enhances in early age but not long-term strength. For 28-day mix F3 had high strength as fly ash adds to long-term strength. When Calcium Hydroxide (CH) formed during cement hydration activates GGBS to form C-S-H gel and additional CH now reacts with PFA to form secondary C-S-H gel which explains the high long-term strength for mix F3.

5.3.2 CEMENT/GGBS/PFA TERNARY MIXES

For ternary mix, PFA was used as a workability agent, which was believed to act as a filler material due to its fine and spherical shaped particles. There was no prior work done which used GGBS and PFA to form a ternary mix with little quantity of cement. The concept of trial mixing was adopted to find the appropriate mix design which would satisfy the fresh and hardened state properties required for this project. The first few mixes were derived with low water/fines ratio and on their results future mixes were derived. The mix F0 showed highly cohesive mix and was consistent and flowable in nature due to high amount of fines present in the mix. Mix F0 had high 7-day strength as large amount of PFA and GGBS proved to enhance particle packing of the mix and PFA even added to long-term strength. For mixes F1, F2, F3 and F4, the cement content and fines content was lowered to minimum quantity and still satisfy the fresh and hardened state properties.

In figure 5.5, a graph between water/fines ratio and strength development of all the cement/GGBS/PFA mixes is shown. From the graph, it can be seen that mixes with water/fines ratio in the range of 0.5 - 1.0 showed high compressive strength and were very consistent and flowable. As the mixes F0, F1 and F2 showed high strengths, then for next mixes F3 and F4, the water/fines ratio was increased to range of 1.2 to 1.5 and cement content was lowered to 15 kg/m³. As the mixes had

less fine present to absorb all the water, it proved hard to be workable and started to segregate when the mix were kept untouched.

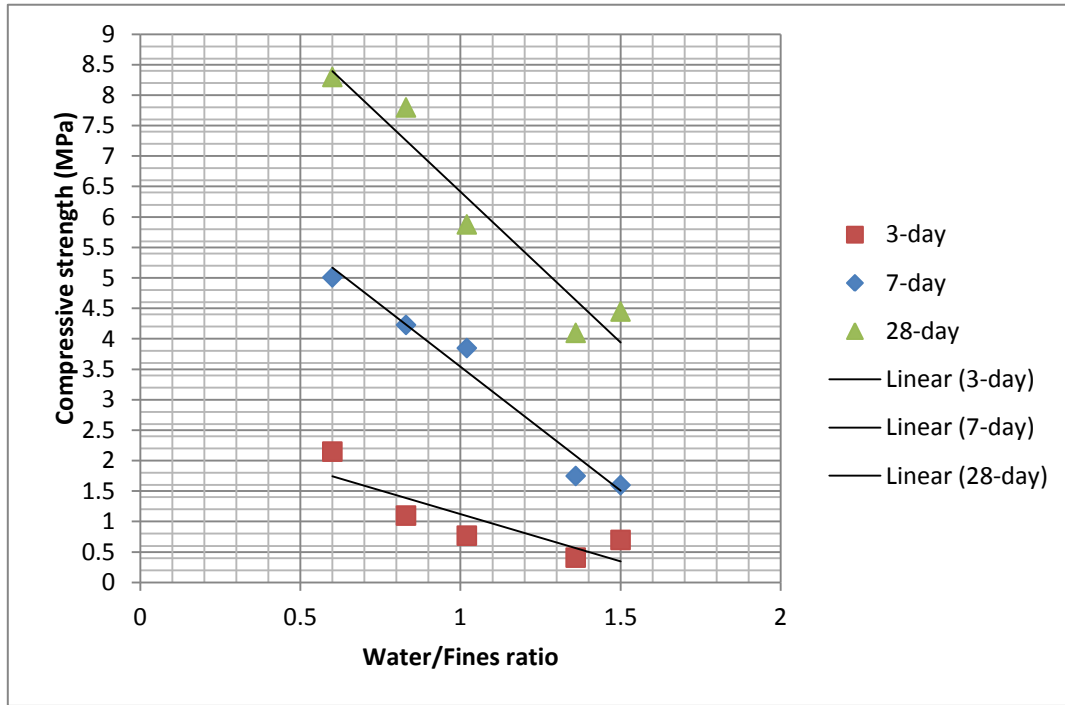


Figure 5.5 – Water/fines ratio versus Compressive strength for cement/GGBS/PFA mixes

As PFA was originally used as a filler material, it showed to increase the long-term strength as seen from the graph in figure 5.5. The mixes showed a high rise in strength for 7-day to 28-day as the PFA reacts with Calcium Hydroxide (CH) produced during GGBS and cement hydration to form C-S-H gel at later age.

The cement/GGBS/PFA ternary mix was difficult to attain both fresh and hardened properties required. The best mix close to satisfy the requirement for this project was F4 which had a compressive strength of 1.6MPa at 7-day as on further increasing the water/fines ratio it would cause the mix to fail in fresh state properties.

5.3.3 CEMENT/GGBS/LIMESTONE DUST TERNARY MIXES

From the previous ternary mixes incorporating PFA as filler material showed increase in long-term strength as it acts a cementitious material at later stage. Now a different filler material was used (i.e. limestone dust) as it was believed to behave as a inert material. There was no previous work done using limestone dust, so trial mixing method was adopted. The first few mixes which were poured had high fines and GGBS content which enhanced the particle packing and did improve the consistency and flowability of the mix. The flow table diameter of mixes was in the required range. The high water/fines ratio of mix L0, L1, L2 and L3 was in range of 0.59 to 1.03, which resulted in high 7-day compressive strength. The next mixes were derived by reducing the water/fines ratio and cement content to minimum range till the mixes are still workable and consistent.

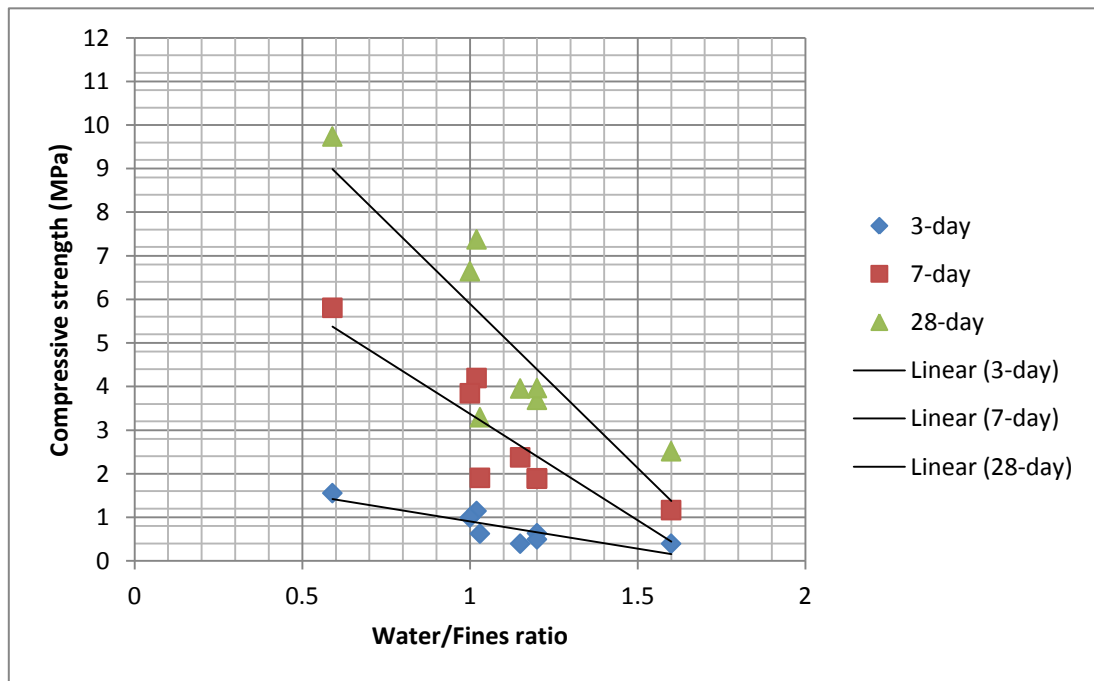


Figure 5.6 – Water/fines ratio versus Compressive strength for cement/GGBS/limestone dust mixes

In figure 5.6, a graph between water/fines and strength development of all cement/GGBS/limestone dust ternary mixes is shown. From, the graph it can be seen that mixes with water/fines ratio in range of 0.6 to 1.3 showed excellent fresh state properties but had a compressive strength of much more than 1MPa for 7-day. The limestone dust improved the packing density of the mix and even added to early age strength by providing nucleation sites for cement and GGBS hydration. Unlike PFA, limestone dust only added to early age strength and did not enhance the strength gain from 7-day to 28-day.

The mix L7 in which the cement content was lowered to 15kg/m^3 and water/fines ratio was increased to 2.10 proved difficult to maintain the consistency as it segregated when left untouched for a while. When the pour was remixed, the free water seemed to have disappeared. The compressive strength for 7-day of mix L7 was the closest to the required limit of 1MPa. On observing the fresh state properties of mix L7, it was clear that the water/fines ratio cannot be increased as the mix would be inconsistent and impossible to work.

CONCLUSIONS

The aim of this project was to optimize the mixture proportions using various filler and cementitious materials for Controlled Low Strength Material (CLSM). The mix proportions of the various filler and cementitious materials that were tested included cement/GGBS, cement/GGBS/PFA, cement/GGBS/limestone dust. From the trial mixes that were carried out with these materials, the following conclusions can be made:

For the cement/GGBS pour, as there was previous work done on this mix, it was confirmed that the presence of GGBS was found to provide lesser consistency and flowability. In this project only one cement/GGBS mix was poured, with a GGBS content of 75% of cement replacement and high water/fines ratio. However, as mentioned in Chapter 4, increasing the water/fines ratio would mean that the target strength of less than 2MPa at 28-days was achieved but the fresh state properties of the mix was not appropriate for the typical CLSM mix. The mix was inconsistent, segregated and a lot of unmixed water was present and the flow table diameter was below the standard range for a CLSM mix (i.e. from 600mm to 700mm). From the previous work it had been seen that at low water/fines ratio and high fines content, a highly flowable and consistent state is possible but the water/cement ratio although low would mean that the target strength of less than 2MPa at 28-day would be exceeded. The American Concrete Institute (ACI-229R 1999), however, defines CLSM as a material with a long-term strength of 8.3MPa or less. This upper limit of 8.3MPa for the material would be used when future excavation is unlikely, such as structural fill underneath buildings. This means that a highly flowable and consistent cement/GGBS CLSM mix could potentially be obtained for structural purposes. As for the requirement of this project, some filler materials was used which would improve the consistency and workability of the cement/GGBS mix and still keep the strength within the target range.

Using the first of the fillers, PFA, cement/GGBS/PFA pours, ternary pours, were done by incorporating various quantities of PFA to the cement/GGBS mix. It was hoped that PFA would improve the workability of the mix due to its fine spherical shaped particles. It was seen from the various mixes poured in Chapter 5 that PFA does improve the consistency and absorbs the free water present in the mix due to its fineness. The fly ash content was varied from 180 kg/m³ to 45kg/m³, mixes with high PFA content worked very well for the fresh state properties but the compressive strength at 28-day was as high as 8MPa. The addition to strength was due to the cementitious nature of PFA, when reacts with Calcium Hydroxide (CH) produced during hydration of cement and GGBS. As observed from the trial mixing, the cement content was reduced to 15 kg/m³ from 30 kg/m³ and the reduced PFA content resulted in decreased the fresh state properties, the mix starts to segregate, heavy bleeding and inconsistent. While the compressive strength at 7-day was measured to be reduced by 50%. It was concluded that PFA improves the fresh state properties of the CLSM mix but does contribute to the long-term strength which is more than the target strength. The PFA content in the range of 80 kg/m³ to 50 kg/m³ and water/fines ratio between 1.3 to 1.6, would result in a consistent and workable mix although with heavy bleeding and the compressive strength at 7-day was slightly above 1MPa. From the trial mixing, it can be concluded that PFA and GGBS together can be used as a cement and sand replacement where there is no need of future excavation for the material, as PFA adds to the long-term strength.

For the cement/GGBS/limestone dust pours, a ternary mixes were derived by incorporating limestone dust into the cement/GGBS CLSM mixes. Limestone dust, which is a largely inert material and a by-product from quarrying, was used to replace PFA from the ternary mix as the workability agent. As discussed in Chapter 5, the limestone dust acted as an excellent workability agent. The limestone, when present in sufficient quantities, acted in a similar manner to PFA, in that it improved the flowability of the pours. Quantities in region of 100-200 kg/m³ provided highly flowable and consistent mixes, but, limestone dust also

improves the early age strength of the material. The limestone dust with GGBS and low cement content resulted in a large increase in 7-day and 28-day strength possibly due to providing nucleation sites for cement hydration. It was believed that high content of fines present in the mix, also improved the particle packing density which imparted strength to the material. Due to its relatively high compressive strengths, the limestone dust was lowered in the next trial mixes from 100 kg/m^3 to 45 kg/m^3 and the water/fines ratio was increased. As the fines were reduced, the absorbing capacity of the mix was less and the mixes were not consistent and flowable. An optimum range of limestone dust was achieved of 60 kg/m^3 to 80 kg/m^3 , where the mixes performed well for the fresh state properties and compressive strength was slightly above the target strength range. Looking at the water/fines ratio, a consistent and flowable mix was acquired in the range of 0.50 – 1.00. During the trial mixing process, these ratios provided an indicator of what was ok required ratio of the water to fines needed to obtain adequate mix designs.

6.1 FUTURE WORK

- During trial mixing process, it was discovered that an important factor which has a significant effect on the behavior of the material, is the particle size of the sand. The used sand in this project was medium sand. As sand approximately makes up of 75% of CLSM, it is important to focus on the type and grade of the sand used. The medium sand is more prone to segregation and bleeding in the CLSM mixes, as high water/cement ratio are used. The coarseness of sand also affects the compressive strength, as there is strict low limit for it in this project. Future work on these ternary mixes derived in the project can be done using a finer sand to understand its other effect on the mixes.
- There are various other filler materials which are waste/co-product from various industries like kiln dust, quarry dust and silica fume. These filler

material could be used in the ternary mixes with cement/GGBS mixes to impart the required workability and target compressive strength to the CLSM mixes.

- The particle packing density of the mixes could be studied. It is believed that the particle packing efficiency has an enormous effect on the properties of fresh and hardened concrete. As the workability and consistency are one of the important parameters for CLSM, particle packing of various fines used could be very essential.

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