

EXPERIMENTAL INVESTIGATION ON USE OF COARSE EAF SLAG AGGREGATE AND GGBFS IN ROLLER COMPACTED CONCRETE PAVEMENT

A Dissertation submitted in fulfillment of the Requirement for the award of the degree of

**MASTER OF ENGINEERING
In INFRASTRUCTURE ENGINEERING**

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DECLARATION

I, Amiya Kumar Thakur hereby declare that the work presented in this thesis entitled “EXPERIMENTAL INVESTIGATION ON USE OF COARSE EAF SLAG AGGREGATE AND GGBFS IN ROLLER COMPACTED CONCRETE PAVEMENT” in fulfillment of the requirement for the award of degree of Master of Engineering in Infrastructure Engineering submitted at Civil Engineering Department, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala is an authentic record of work carried out under supervision of Sh. Dinesh Ganvir (Principal Scientist & HOD, Rigid Pavement Division, CSIR-CRRI), Dr. Prem Pal Bansal (Professor & HOD, Civil Engineering Department, Thapar University) & Dr. Tanuj Chopra (Assistant Professor, Civil Engineering Department, Thapar University) from 2021 to 2022. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.


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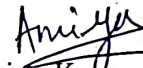
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ABSTRACT

The present study investigates the effect of partial and full replacement of natural coarse aggregate with coarse electric arc furnace (EAF) slag aggregate and partial replacement of cement with ground granulated blast furnace slag (GGBFS) on the mechanical and durability properties of roller compacted concrete pavement (RCCP). The replacement level of EAF slag aggregate were at five levels (i.e. 0% ,25% ,50%,75% & 100%) and of GGBFS was (0 % ,30 % ,50% & 70%). The EAF slag aggregate were stabilized by exposing to outdoor condition for several years and the volumetric expansion test using steam exposure device was done to check volume stability. Soil compaction method was used for mix proportioning of RCCP. The fresh properties of RCCP investigated were fresh density and modified vebe test was done to measure the consistency of concrete. For investigating the mechanical properties various test were done at 7 and 28 days (i.e. Compressive strength, split tensile strength, flexure strength modulus of elasticity) and also non-destructive testing was done at 28 days (i.e. Ultra pulse velocity test (UPV) & rebound hammer test). The durability test done at 28 days were water absorption, skid resistance, abrasion resistance, carbonation & hot water curing. The results showed that with the increase in slag aggregate percentage there was increase in the fresh density of concrete and also slight increase in the vebe time but with the increase in GGBFS percentage the vebe time decreased and the fresh density increased upto 30 % GGBFS replacement. The mechanical strength properties improved with the increase in slag aggregate percentage but with the increase in GGBFS percentage it decreased when compared to 100 % cement mixes. In UPV test and rebound hammer test all the mixes showed excellent quality of concrete except mixtures containing 70 % GGBFS. In durability water absorption, skid resistance and abrasion resistance increased with increase in slag aggregate percentage whereas with GGBFS mixes these properties decreased. The carbonation and hot water curing had negligible effect on RCCP containing EAF slag aggregate. Till 50 % GGBFS replacement & 100 % EAF slag aggregate replacement all the results of mechanical properties and durability properties were comparable to control mix.

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Compressive Strength = L_d/A_c	Equation (4.1)	62
Flexure strength = $P l / b d^2$	Equation (4.2)	67
Flexure strength = $3P a / b d^2$	Equation (4.3)	68
Split Tensile Strength = $2P/\pi LD$	Equation (4.4)	71
$y = 1.7252x - 26.59$	Equation (4.5)	80

LIST OF ABBREVIATIONS

AOD	Argon Oxygen Decarburization
BFS	Blast Furnace Slag
BOF	Blast Oxygen Furnace
BOFS	Basic Oxygen Furnace Slag
BPT	British Pendulum Test
C ₂ S	Di- Calcium Silicate
C ₃ S	Tri- Calcium Silicate
CaCO ₃	Calcium Carbonate
CaF ₂	Calcium Fluoride
CaO	Calcium Oxide (Lime)
CaOH	Calcium Hydroxide
CEAFS	Coarse Electric Arc Furnace Slag
CO ₂	Carbon Dioxide
CSH	Calcium Silicate Hydrate
EAF	Electric Arc Furnace
FeO	Ferrous Oxide
FST	Final Setting Time
GGBFS	Ground Granulated Blast Furnace Slag
HMA	Hot Mix Asphalt
IST	Initial Setting Time
ITZ	Interfacial Transition Zone
LDF	Ladle Furnace

LMF	Ladle Metallurgy Furnace
LOP	Limit of Proportionality
LVDT	Linearly Varying Differential Transducer
MDD	Maximum Dry Density
NA	Natural Aggregate
OHF	Open Hearth Furnace
OMC	Optimum Moisture Content
OPC	Ordinary Portland Cement
RCC	Roller Compacted Concrete
RCCP	Roller Compacted Concrete Pavement
RCPT	Rapid Chloride Permeability Test
SiO ₂	Silicon Dioxide
SMA	Stone Matrix Asphalt
UPV	Ultrasonic Pulse Velocity
UTM	Universal Testing Machine
XRD	X-Ray Diffraction

LIST OF SYMBOLS

A_c	Area of Cross-Section (mm^2)
L_d	Load (N)
P	Maximum Load (N)
l	Span on which beam is supported (mm)
b	Width of Specimen (mm)
d	Depth of Specimen
L	Length of Specimen (mm)
D	Diameter of Specimen (mm)
T	Transit Time (μs)
V	Velocity (km/s)

CHAPTER 1

INTRODUCTION

1.1 GENERAL

RCC is zero-slump concrete that is generally used because of its speedy construction technique and low cost (M. N.-T. Lam et al., 2018a) . RCC found significant application for low-speed concrete pavements in places like parking areas, port areas, and storage facilities, military highways, and industrial manufacturing areas are all examples of this (Vahedifard et al., 2010). In RCCP the concrete is compacted at maximum dry density(MDD) using vibratory or pneumatic tired rollers & optimum moisture content(OMC) is found using Superpave gyratory, vibrating hammer & modified proctor(Şengün et al., 2019).The important property of RCC is workability which tells the amount of energy that will be required for MDD. Dowel bar, tie bar and surface finish is not required in these type of concrete.Because of which RCCP requires less equipment and can be placed in a more efficient manner(Tayabji and Sherman).But to make a good RCC profile and smoothness diamond grinding is used so that the pavement can carry high speed traffic(Aghaeipour and Madhkhan, 2020).

Over the previous 10 years, global steel production has expanded fast, with roughly 1560, 1650, and 1670 million tonnes of crude steel produced in 2012, 2013, and 2014, respectively(M. N.-T. Lam et al., 2018b). Each tonne of steel produced generates 2-3 tonne waste either in solid, liquid or gaseous form which has created a problem with handling and disposal of these wastes.In India 8Mt of steel slag is produced by VISL,DSP and BSP plants as per financial year 2014-2015(Dhoble and Ahmed, 2018).Ferro scrap nigam limited a subsidiary of MSTC limited in its reports published that 23.39 lakh tonne of steel & iron scrap has been generated in year 2017-2018.Main three types of slag producing furnaces are blast oxygen furnace, electric arc furnace & ladle metallurgy furnace(Brand and Roesler, 2015; Rooholamini et al., 2019). Steel manufacturing process has EAF slag as a by-product; each tonne of liquid steel produces roughly 150–200 kg of EAF slag(M. N.-T. Lam et al., 2018b). In certain parts of the United States, there have been shortages of high-quality natural aggregates. According to one projection, the global concrete industry would require 8–12 billion tonnes of natural aggregate per year beyond 2010(Piemonti et al., 2021).Some ionic contaminants of water i.e. phosphate and ammonium ions are removed by sorbents that are produced by steel slag aggregate and hence reduces the environment pollution(Rondi et al., 2016).Steel slag is also used now a days in CO₂ sequestration , soil treatment and sewage

treatment(Li et al., 2022).As steel slag aggregate can be used as substitute to N.A to solve the problem of shortage of aggregates and utilisation of soild by- products as they are having good engineering properties(Arivoli and Malathy, 2017; Mo et al., 2020).RCCP comprises 75 % of aggregate volume in total thus we can substitute natural aggregates using EAF slag aggregates to produce environment-friendly concrete(M. Lam et al., 2018; M. N.-T. Lam et al., 2018a).Steel slag aggregate has good mechanical properties & physical properties except high water absorption because of these properties they are used as aggregates in asphalt paving road mixtures(Padmanaban et al., 2020).Slag aggregates can be used as a fine or as a coarse aggregate in concrete because it increases the specific bulk density of concrete and concrete produced of coarse slag aggregate has more compressive as compared to fine aggregate concrete(Gencel et al., 2021).The property of steel slag is having high variability due to the change in properties of basic raw material that is used for making iron hence it effects the bonding condition and influences the composite proformance(Brand and Fanijo, 2020).Studies and experiments are being carried out to use in concrete. Steel slag aggregate's sole drawback is its expansive properties & products formed after the reaction of concrete and slag(Patel, 2008). This expansive property is due to free magnesia (MgO) and lime(CaO) in aggregate and this can be overcome by leaving the aggregate in an open atmosphere for a long period i. e. more than 2 years to form stable hydrates and carbonates(Papayianni and Anastasiou, 2011). Carbonation is also a method to reduce the free Cao & MgO content in slag concrete(Pang et al., 2015).

Out of total global CO₂ emission ,5% is being contributed by the cement industry only.The production of one tonne of cement leads to 0.65 to 0.90 tonnes of CO₂ emission(Scrivener, 2014).After china India is the largest country in cement production as per records India produced 410 million tonnes of cement(Statistics Portal 2021,Indian Brand equity foundation. Research on concrete has also been significantly influenced with this awareness in many ways specifically by encouraging the utilization of supplementary cementitious materials. Many supplementary cementitious mineral admixtures such as GGBS, Fly ash, Nano-silica, metakaolin are industrial waste & their disposal is not an easy process hence they should be utilized in concrete to make it environmentally friendly and cost-effective(Saluja et al., 2019).

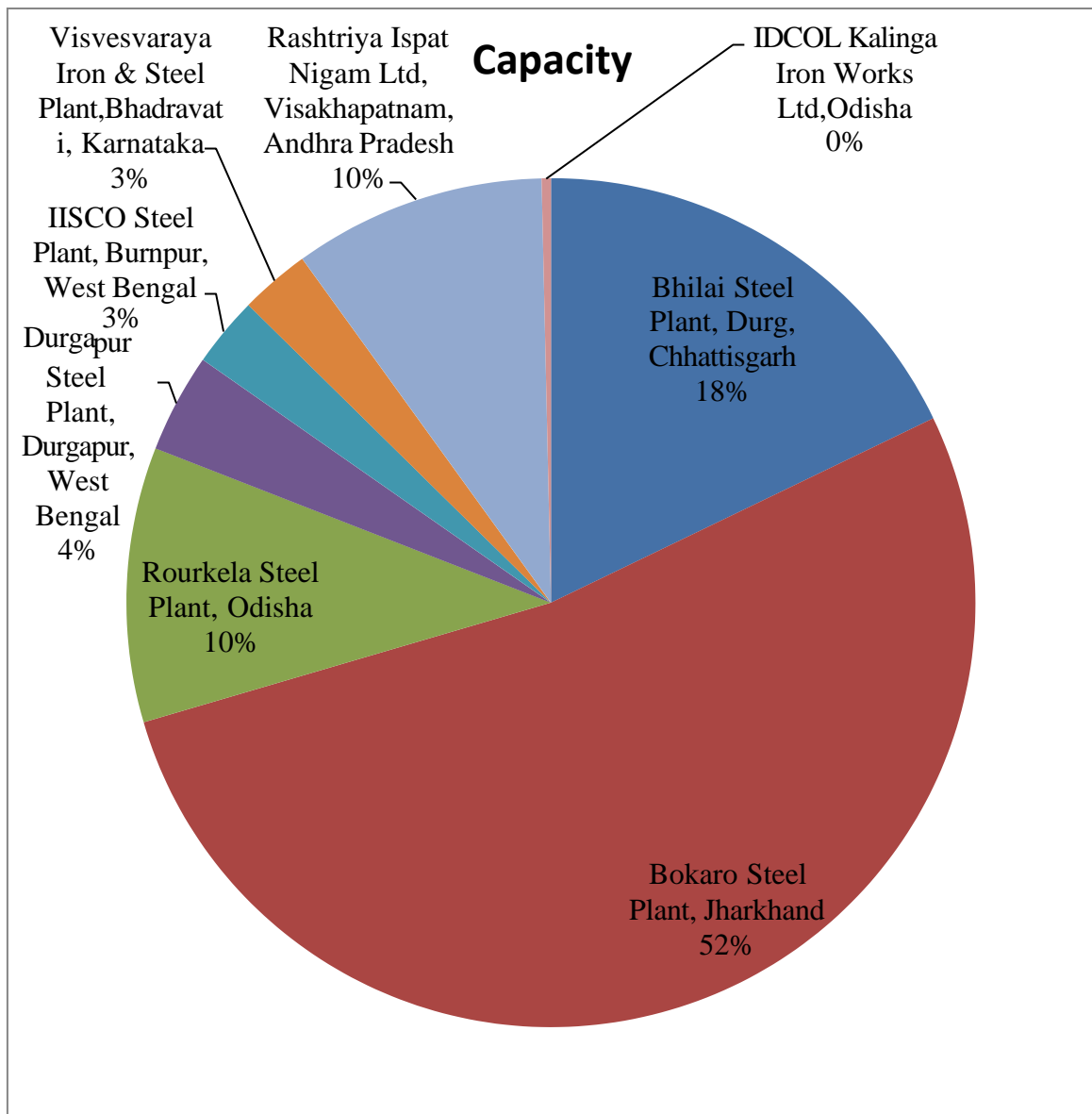


Figure 1.1 Production of steel slag aggregate in various steel plants (Dhoble and Ahmed, 2018)

Out of all these materials fly ash is the most researched and commercially sold pozzolan. Because of their fineness and the pozzolanic reaction they make the matrix dense by filling the pores and hence reduce the permeability as well as free lime is utilized (M. N.-T. Lam et al., 2018b; Mardani-Aghabaglou and Ramyar, 2013; Papayianni and Anastasiou, 2011; Research Scholar, Civil Engineering, JNTUH, Hyderabad, Telangana, India. et al., 2015; Saluja et al., 2019). Concrete having optimum Fly ash 20 % of total cementitious material and EAF slag aggregate 50% of natural aggregates produced a compressive strength of more than 35MPa (Lam et al., 2017, 2020; M. N.-T. Lam et al., 2018b).

1.2 NEED FOR RESEARCH

From last 10-15 years many of the researchers are working on steel slag aggregate and mainly they are focusing on the utilization of the expansive compounds present in steel slag

aggregate to make it volumetric stable. In pavement concrete some researchers have successfully used coarse EAF slag aggregate with some of the SCMs. But only few are there who have tried to utilise coarse EAF slag aggregate in RCCP and the SCM used was fly ash only. At present there are no codes for the using slag aggregates in RCCP. Main reason for this could be lack of sufficient data regarding the efficiency of steel slag aggregate in RCCP. Therefore, this dissertation focuses on the utilization of EAF slag aggregates and GGBFS that are by- products of JSW steel plant (Dolvi,Maharashtra) in RCCP. The data thus generated would be useful in development of Indian codes for steel slag aggregate.

1.3 OBJECTIVES

Objective of the study is to experimentally investigate the strength & durability properties of RCCP incorporating coarse EAF slag aggregate.

1.4 SCOPE

To achieve the above objective, the scope of the present study comprise of:

1. Characterization of EAF slag aggregate.
2. Mix design of EAF slag aggregate roller compacted concrete using GGBFS.
3. Studying the effect on Fresh properties ,workability, Mechanical strength properties and durability properties of RCCP

1.5 METHODOLOGY

1. Production of EAF steel slag aggregates from JSW steel plant at Dolvi, Maharashtra and volumetric stabilization of steel slag aggregate at CSIR- CRRI.
2. Experimentally characterising the EAF slag aggregate and comparison of same with the Natural aggregate. The properties studied are particle size distribution, specific gravity, soundness, impact value, crushing value, abrasion value, bulk density, water absorption, volumetric expansion of slag aggregate. Characterization was done for cement and GGBFS.
3. Combined gradation of coarse EAF slag aggregate, fine & coarse natural aggregate for different mixes.
4. Modified proctor test for determining the optimum moisture content for different mixes.
5. Mix design was done as per ACI 211.3R. RCCP was produced with different replacement levels of coarse EAF slag aggregate 0% ,25% ,50%,75% & 100 % and

partial replacement of cement was done with GGBFS at 0% ,30%, 50% & 70%.Total number of mix were 20 with these combination.

4. Study of Fresh density of RCCP, workability of RCCP (i.e. vebe time), mechanical strength properties (i.e. Compressive Strength, Flexural Strength, Split Tensile strength, Modulus of elasticity), non – destructive testing (i.e. Rebound Hammer & UPV) and durability properties of RCCP (i.e. Abrasion resistance, water absorption, skid resistance ,carbonation & hot water curing). All these properties are compared with the respective reference mixes.
5. Conclusion on all the above stated properties of RCCP.

1.6 ORGANIZATION OF DISSERTATION

The Dissertation is organized in six chapters based on the studies carried out during research.

The General, Need for research, Research objective, Scope of research & methodology adopted are discussed in chapter 1.

In chapter 2 a detailed state of art is presented. About different types of slag aggregate, characterization of slag aggregate, characterising GGBFS , about modified proctor test for O.M.C, about workability of RCCP , about mechanical strength properties and durability properties has been reviewed in this chapter and based on this detailed literature review the research gap has been identified.

Chapter 3 discusses about characterization of materials used i.e. cement, GGBFS, EAF slag aggregate, natural aggregate. Mix proportioning of the 20 different mixes, modified proctor test performed for all the mixes and the samples prepared for strength test and durability tests are also discussed in this chapter.

In Chapter 4 a detailed presentation is given for the experimental investigation on RCCP incorporating EAF slag aggregate and GGBFS, including the detailed test procedure and results. A thorough discussion was done on fresh properties , mechanical strength properties and durability properties of RCCP in this chapter.

In chapter 5 i.e. the last chapter, gives the overall conclusion drawn from the research & the scope of future research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter different types of steel slag aggregate with their physical and chemical properties are discussed, use of steel slag aggregate, measuring of volumetric expansion in slag aggregate, stabilization of slag aggregate, comparison of physical ,mechanical and chemical properties of slag aggregate and natural aggregate, comparison of mechanical strength properties and durability properties of slag aggregate concrete with conventional concrete and RCC containing slag aggregate with conventional RCC are also discussed in this chapter. At the end of this chapter research gap is also identified.

2.2 TYPES OF STEEL SLAG AGGREGATE

According to the production process, iron and steelmaking slags are usually categorized into Six categories(Piemonti et al., 2021):

2.2.1 Blast furnace slag (BFS)

BFS is formed when iron ore is melted and converted to molten pig iron in blast furnaces(Das et al., 2022). There are two types of BF slag one is air-cooled and the other is granulated slag. Air-cooled slag is formed by cooling molten slag in open pits and it forms like crushed stones whereas Granulated slag is formed by cooling using water jets & it looks like sand. Coarse BF slag aggregate is made by crushing air-cooled slag and then classifying via screens & granulated slags are crushed lightly to make fine aggregate and then they are classified via screens(Miyamoto et al., 2015).

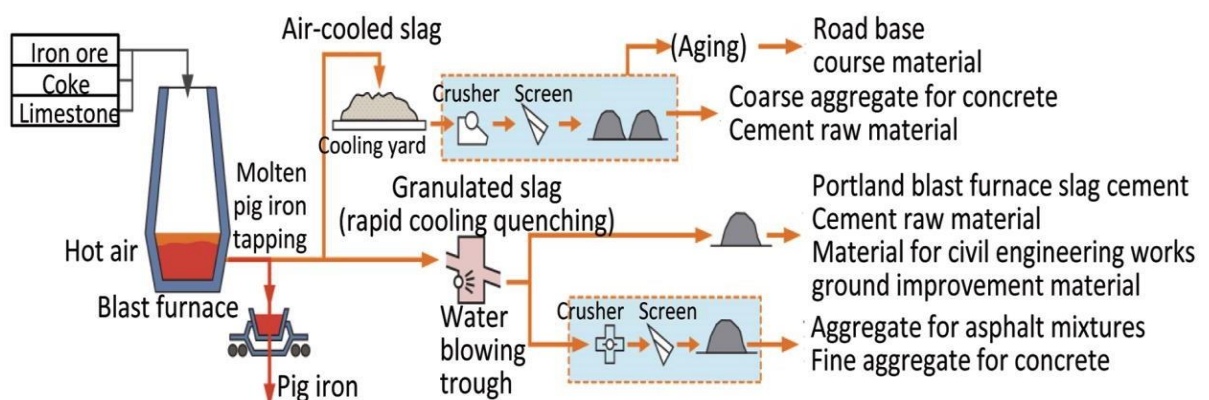


Figure 2.1 Production flow of the blast furnace slag(Miyamoto et al., 2015)

2.2.2 Basic oxygen furnace slag

BOFS process is also known as Linz–Donawitz (LD)(Brand and Fanijo, 2020). The hot liquid metal from the blast furnace, scrap, and fluxes including lime (CaO) and MgO.CaO are charged to a furnace in the Basic Oxygen Furnace (BOF)(Patel, 2008). A lance injects oxygen into the charge, eliminating impurities through by-product gases like CO and molten slag is formed(Brand and Fanijo, 2020). The liquid steel is dumped through a tap into a ladle at the end of the refining process, while the slag is maintained in the tank and transferred into a separate tank through tap (Shi, 2004).

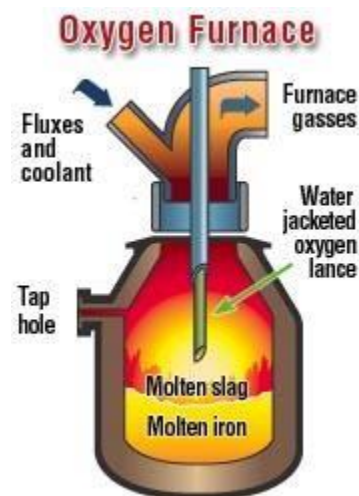


Figure 2.2 Basic Oxygen Furnace(Patel, 2008)

2.2.3 Electric Arc Furnace slag (EAF)

In EAF initially cold charge, recycled steel & fluxing agents are added(Brand and Fanijo, 2020). Three graphite electrodes are used in the furnace through which current is passed and heat is generated which melts the scrap(Shi, 2004).By injecting oxygen, the impurities are removed & to make steel purer additionally alloys are added. The molten crude steel is ladled, while the slag in its molten form is removed through taps (Brand and Fanijo, 2020). This EAF slag is further treated so that it can be used in making concrete by the following process: (1) water is sprinkled and it is turned up and down within 2 days; (2) size is reduced by crushing; (3) size greater than 25 mm are separated and rejected; (4) metallic elements are separated; (5) classification by screening in 3 different fractions; and (6) storage in silos(San-José et al., 2014).

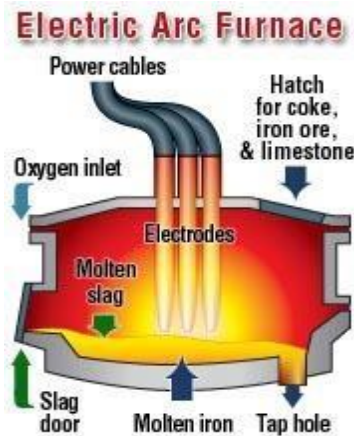


Figure 2.3 Electric Arc Furnace (Patel, 2008)

2.2.4 Ladle metallurgy Furnace

LDF is the further refining process for EAF slag. The LMF process is identical to the EAF process, with the exception that it incorporates extra improvements. To eliminate any remaining impurities and correct the steel chemistry, molten crude steel fluxing agent are added with alloys (Brand and Fanijo, 2020). The chemical composition of ladle slag differs greatly from that of steel furnace slag due to the lower FeO level of the former. Al is used in several steel-making processes for further refinement. The Al₂O₃ concentration of the ladle slag is high in these circumstances. In other processes, CaF₂ is used for further refining, and the ladle slag is mostly made up of CaO and SiO₂ (Shi, 2004).

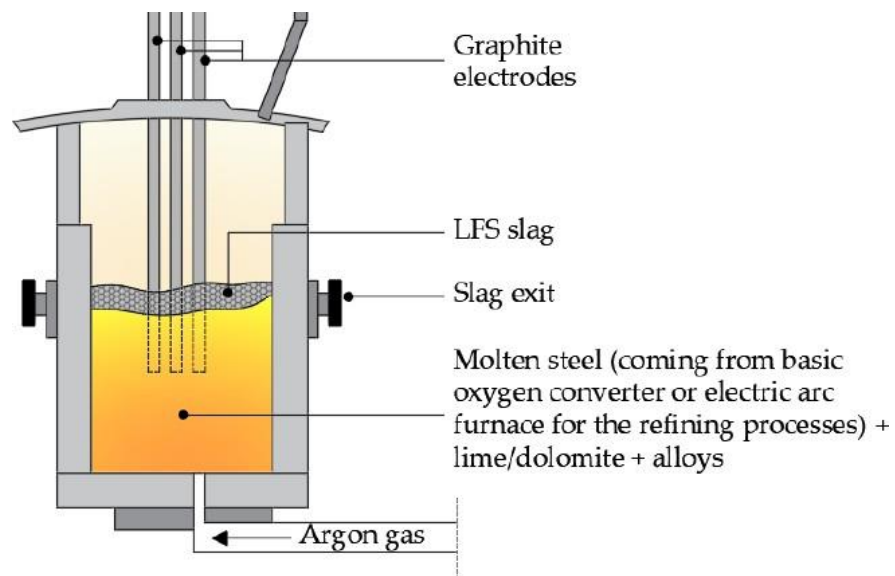


Figure 2.4 Ladle Furnace (Piemonti et al., 2021)

2.2.5 Open Hearth Furnace (OHF)

The BOF and EAF procedures have essentially superseded this method as it is outdated. The OHF process still produces around 0.4 percent of all steel in the world (Brand and Fanijo, 2020).

2.2.6 Argon oxygen decarburization (AOD)

The EAF process is commonly used to start the recycling of stainless steels, followed by the AOD process. The decarburization, reduction, and desulfurization steps of the AOD process refine the molten metal. This technique produces a slag with a high calcium and silicon content, as well as more fluorine and chromium than EAF and BOF slags (Brand and Fanijo, 2020).

Table 2.1 Physical properties of steel slag aggregate (Brand and Fanijo, 2020)

Physical Properties	Units	Granulated Blast Furnace Slag	Air-Cooled Blast Furnace Slag	Basic oxygen Furnace slag	Electric Arc Furnace slag	Ladle Furnace Slag
Dimension	mm	≤0.063	0-4.75	0.16-4.75	0.063-4.75	0.063–0.600
Density	Kg/m ³	2810-2955	2630	3100-3600	2840-3854	2555–3030
Surface Area	cm ² /g	4000-4720	-	4510-4530	4990-5050	1200–8490
Fineness Modulus	%	2.37-3.35	3.02;3.1	2.08-2.80	2.83-7.78	-
Blaine Fineness	cm ² /g	3800-5502	-	-	-	3000
Porosity	%	-	41	-	7.8-14.4	-
Water Absorption	%	2.1	3.45	0.70-4.23	0.18-10.5	-
Water Content	%	-	0.35	1.56-13	-	-
Loss on ignition(LOI)	%	1.08;1.11	-	-	-	-

Table 2.2 Chemical properties of steel slag aggregate (Brand and Fanijo, 2020)

Chemical Properties	Units	Granulated Blast Furnace Slag	Basic oxygen Furnace	Electric Arc Furnace (Carbon Steel)	Ladle Furnace Slag
CaO	%	38.26	42.59	27.71	53.29
SiO ₂	%	34.03	13.59	16.23	20.86
FeO+Fe ₂ O ₃	%	0.74	25.73	33.05	1.75
Al ₂ O ₃	%	11.39	3.59	8.34	10.95
MgO	%	8.65	7.91	5.21	7.18
MnO	%	0.92	2.77	4.57	2.76
SO ₃	%	0.62	0.40	0.13	1.25
TiO ₂	%	3.58	1.71	0.70	0.29
P ₂ O ₅	%	-	1.32	1.76	0.10
Na ₂ O+K ₂ O	%	0.48	-	0.05	1.38
Cr ₂ O ₃	%	-	-	2.57	0.45

Cr ₂ O ₅	%	-	0.02	2.73	-
ZnO	%	-	-	0.44	-
Free CaO	%	-	5.51	0.96	0.78
Free MgO	%	-	-	0.40	-

2.3 USE OF STEEL SLAG AGGREGATE

- i. Blast furnace slag (GBS & ABS) is used in cement production as well as a binding material in concrete. The reuse rate of BFS in Europe is 94 -100% out of which 72 % is used in the manufacturing of cement. (Piemonti et al., 2021).
- ii. In unbound applications, BOF slags are frequently employed as an aggregate such as in road construction. Their usage as replacement of natural aggregate in concrete production is feasible, although it is complex due to the granules' volumetric expansion(Piemonti et al., 2021).
- iii. The EAF slag can be used in concrete production as partial replacement for cement and aggregates. Because of their low hydraulic characteristics and volumetric instability, reusing the LFS for concrete manufacture is challenging. However, employing particular alkaline activators, a few experiments have shown that LFS may be used in concrete requiring minimal mechanical strength as partial replacement for cement (Piemonti et al., 2021).
- iv. Steel slag can be used as a aggregate in hot mix asphalt (HMA) surface mixtures because of its strong frictional and skid resistance properties. Because the particle-to-particle contact of the aggregates does not break during the mixing, laying down, or compaction processes, it is also used to create Stone Matrix Asphalt(SMA)(Patel, 2008).
- v. Steel slag aggregate is also utilized in agriculture since it contains vital plant nutrients such as iron, manganese, magnesium, zinc, and molybdenum. Steel slag aggregates are used for soil stability or soil enhancement, as well as for industrial wastewater run-off remediation(Patel, 2008).

2.4 PHYSICAL PROPERTY OF STEEL SLAG AGGREGATE

2.4.1 Shape & Size

Steel slag aggregates are generally cubical, angular fragments with flat or elongated forms. They have a large surface area than smoother aggregates of same volume because of rough vesicular structure with numerous unconnected cells; this property offers a good bond with concrete(Patel, 2008). As they are angular they have very good interlocking properties.

2.4.2 Specific Gravity

Steel slag has adequate concentrations of iron oxide (FeO), hence it has a higher specific gravity value than natural aggregates. Steel slag is almost 20% heavier than minerals like limestone and granite (Aziz et al., 2014). IS 2386 part 3 & ASTM C128 -01 is used to determine the specific gravity of aggregate. EAF oxidizing slag has high specific gravity and, when utilized as an aggregate in structural concrete, yield heavyweight concrete (Sekaran et al., 2015). As shown in Figure 2.5.

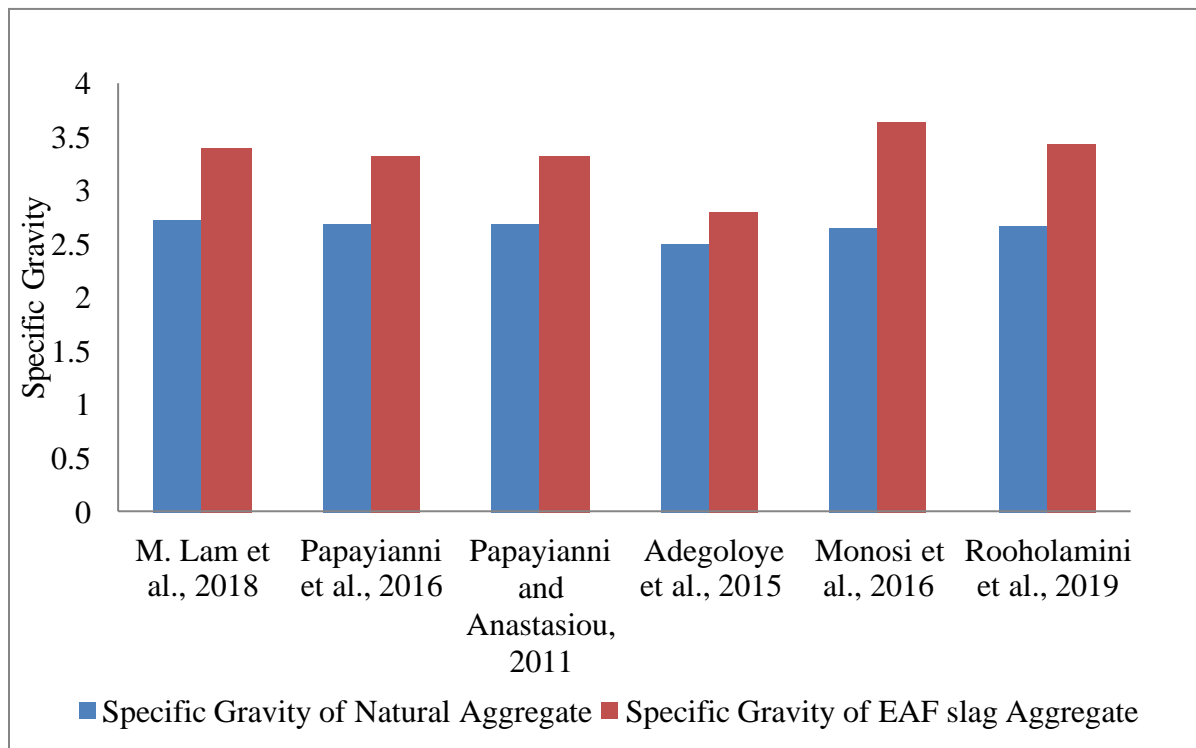


Figure 2.5 Specific Gravity

2.4.3 Water Absorption

Since slag aggregates are porous hence they have high water absorption compared to natural aggregates as shown in Figure 2.6. Because of high water absorption, a relationship was established between time and the water absorbed to make a good mix (M. Lam et al., 2018).

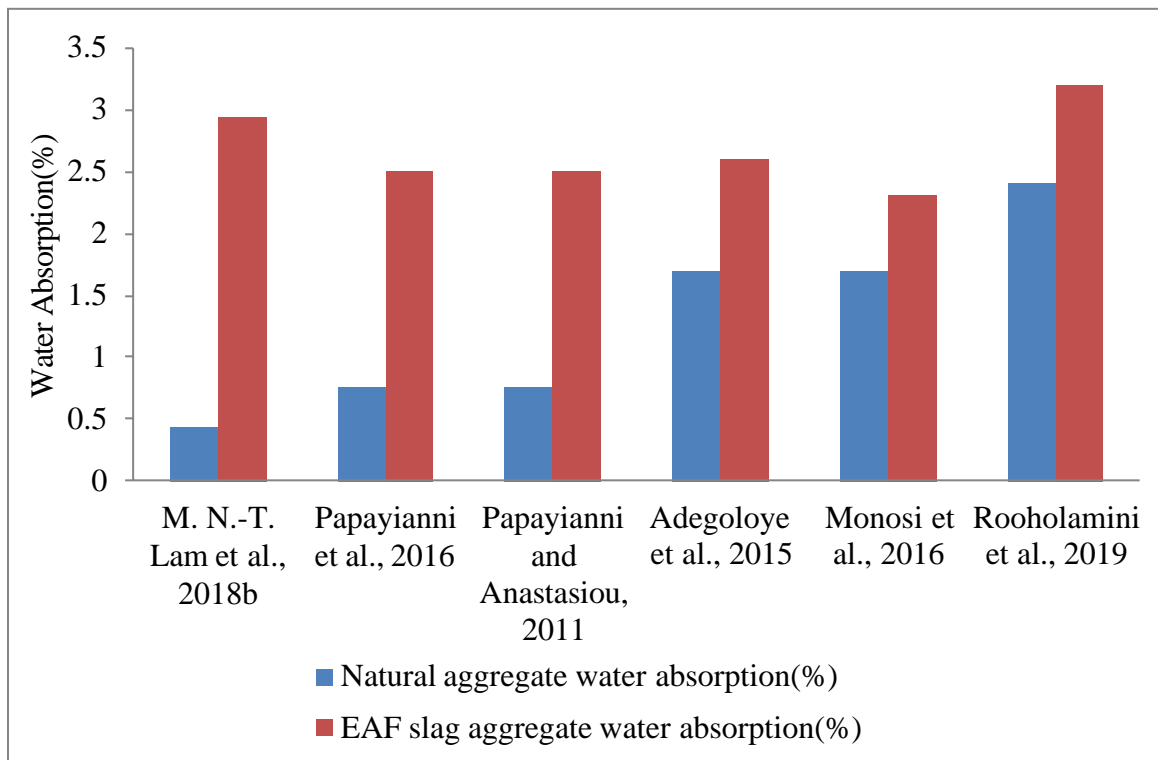


Figure 2.6 Water Absorption

2.4.4 Bulk Density

EAF Slag aggregate is having good gradation as compared to natural aggregate hence EAF Slag aggregate gets densely packed. Because of higher bulk density, the unit wt. of concrete produced is more (Papayianni and Anastasiou, 2011).

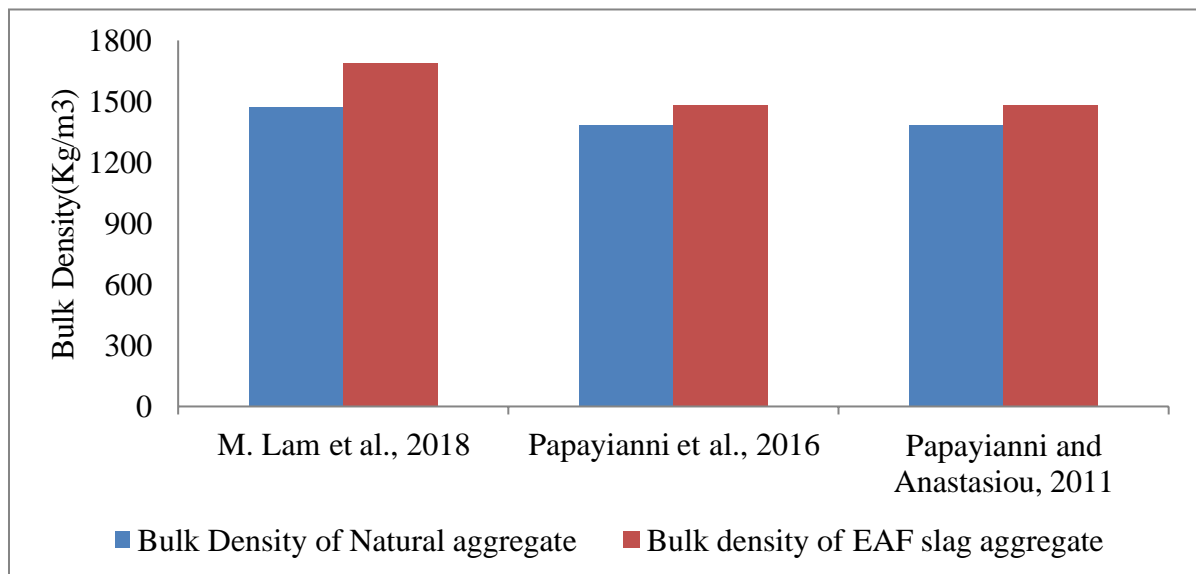


Figure 2.7 Bulk Density

2.5 MECHANICAL PROPERTIES OF STEEL SLAG AGGREGATE

Steel slag aggregates exhibit good fragmentation resistance and meet the standards for abrasion-resistant concrete (Papayianni et al., 2016). In general steel slag aggregate has a

better abrasion and impact value as compared to natural aggregate(Tarawneh, 2014). Since the slag aggregate are having more unit weight they have high toughness and greater resistance to shear a compared to natural aggregate.

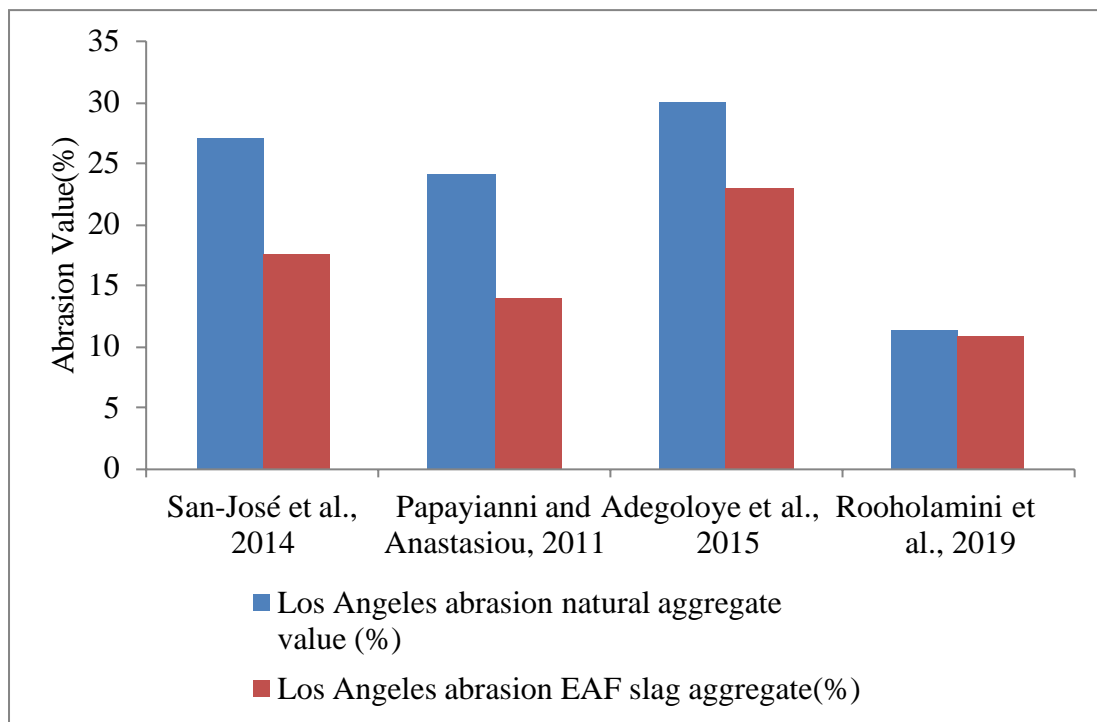


Figure.2.8 Mechanical Properties of Aggregate

2.6 CHEMICAL PROPERTY OF STEEL SLAG AGGREGATE

Steel slag aggregate is block-shaped with a honeycomb structure as well as a high porosity. The majority of steel slag is composed of calcium oxide, Magnesium oxide, Silica dioxide, and Iron oxide. The concentration in liquid slags of above mentioned oxides in low-phosphorus steelmaking practice is in the range of 88–92 percent. As a result, the steel slag may be represented simply by the CaO–MgO–SiO₂–FeO quaternary system(Wang et al., 2010).As EAF slag has high crystallinity & its by-products has not showed any pozzolanic property therefore they not used as active addition in manufacturing of cement or concrete(Frias Rojas and Sánchez de Rojas, 2004).XRD & complexometric titration(Using ethylene glycol) is used to determine the free lime(Brand and Fanijo, 2020). Some researchers suggested selective extraction methods for measuring free MgO, such as K₂Cr₂O₇, NH₄NO₃, or C₂H₆O₂ with I₂ and C₂H₅OH, while others recommended solid-state ²⁵Mg nuclear magnetic resonance spectroscopy or petrographic approaches & XRD(Brand and Fanijo, 2020).The cementious property of steel slag can be improved by reprocessing it by remelting and water quenching and hence there is reduction in FeO content and increase

in merwinite phase which is highly reactive with lime and forms tobermorite gel (Muhmood et al., 2009).

Table.2.3 Chemical Property of Slag Aggregate

Element	M.A. González-Ortega et al.	(Lee et al., 2019)	(Wang et al., 2010)	(Brand and Fanijo, 2020)
CaO	30.2	20.6	35-60	25-35
Fe ₂ O ₃	25.8	37.3	15-30	20-30
SiO ₂	19.0	16.1	9-20	8-18
Al ₂ O ₃	12.7	12	2-9	3-10
MnO	4.8	5.6	3-10	2-8
MgO	4.6	4.4	5-15	2-9
Cr ₂ O ₃	1.6	-	-	0.5-2.2
TiO ₂	1.0	0.7	-	-
BaSO ₄	-	-	-	-
SrO	-	-	-	-

2.7 VOLUME EXPANSION IN SLAG AGGREGATE

The potential expansion of the aggregate is mostly caused by iron nodules and unreacted calcium and magnesium oxides found in the EAF slag. When calcium oxide comes into contact with water, it hydrates, causing a fast volumetric expansion (González-Ortega et al., 2019). The reaction of free lime with water is given as :



The reaction proceed to the right-hand side at room temperature.

Only at 547 °C or above does the reaction move to the left hand. By 97.92 % there was growth in absolute volume of solid phase (Wang et al., 2010). The free form of MgO (periclase) is volumetrically unstable and can only be generated in conditions of low basicity. MgO, FeO, and MnO commonly form solid solutions due to the high basicity condition in molten steel slag and the near radii of Mg⁺⁺, Fe⁺⁺, and Mn⁺⁺ (0.78, 0.83, and 0.91Å) (Wang et al., 2010). Additional expansion phenomena have been attributed to β-dicalcium silicate conversion to γ-dicalcium silicate, oxidation of FeO to Fe₃O₄, carbonation of oxide,

hydroxide phases, hydration of silicate, sulphide phases, or rust development from metallic inclusions. Extra hydration products, such as calcium monocarboaluminate, CaCO_3 , hexagonal calcium aluminate hydrates, hydrogarnet, and CSH, have also been found, however, it is unknown if and how much these additional hydration products contribute to expansion (Brand and Fanijo, 2020). EAF was far better because it was having less CaO & MgO content hence it showed a less expansive nature as compared to BOF & LMF slag (Brand and Roesler, 2015).

Different methods are used to find the volume expansion, Some are bound tests and some are unbound test :

2.7.1 Autoclave Expansion test

This test uses rapid catalytic high-temperature technology which conforms to ASTM C151. The specimen is kept in a mould at a constant temperature & humidity and heating catalysis was performed at 100°C and 100 percent relative humidity & every day the change in length was to be measured. The readings were taken for 96 hours (Kuo et al., 2014). While this expansion value does not always correspond with field performance or CaO content, it is a quick test approach that may be used as an index test. Furthermore, autoclaving conditions can be employed to analyse the hydration processes in Steel furnace slag (Brand and Fanijo, 2020).

2.7.2 Expansion force test (EFT)

The EFT technique was developed to measure the expansion force generated by a fixed volume of coarse slag aggregate while keeping the volume change to a minimum. In a cylindrical mould the SFS aggregates are compacted and submerged in water at 74°C in this test, and the force generated by the expanding aggregate is monitored using a load cell. These data may be used to determine the tensile stresses caused by a single expanding SFS particle, which can then be utilized to evaluate the "usability criteria" of the steel furnace slag aggregates to be employed in bound applications (Brand and Fanijo, 2020).

2.7.3 Disruption ratio test

Parallel to the expansion force test, a autoclave disruption test has been designed to examine individual coarse steel aggregate particle volumetric stability. In this test, a steel slag particle is split into different fragments and petrographically analysed. Specific quantities of slag particles, typically 100 or 50, are selected to evaluate each fraction size of the slag.



Figure 2.9 Apparatus for Expansion force test(Wang, 2010)

After that for testing the slag sample is put in an autoclave. For 1 hour of testing, the autoclave was set to 357 kPa and 137°C. The pressure is roughly 3.5 atm, and it was chosen to be in the middle of the range of the autoclave used in the test. The disruption eq. is

$$R=(N_c/N_t)*100$$

Where, N_c denotes the quantity of particles broken after the test, and N_t denotes the number of particles chosen for the test (Wang, 2010).



Figure 2.10 Apparatus for Disruption Test (Wang, 2010)

2.7.4 Potential expansion of aggregate from Hydration reaction

This test conforms to ASTM D4792(Frías et al., 2010). Three test specimens were crushed in a 6-in cylinder mould at their optimal moisture level to achieve maximum density. The testing moulds were kept in water at 70 ± 3 °C to speed up the hydration reaction. The initial dial gauge readings were taken after 30 minutes. Daily for 14 days, the volume expansion was estimated by dividing the change in daily dial gauge readings and base readings by the initial specimen height(116.43mm)(Lam et al., 2017). ASTM D2940 recommended that the expansion of steel furnace slag aggregates be ≤ 0.50 percent per ASTM D4792 for use as a graded material in pavement bases(Brand and Fanijo, 2020).

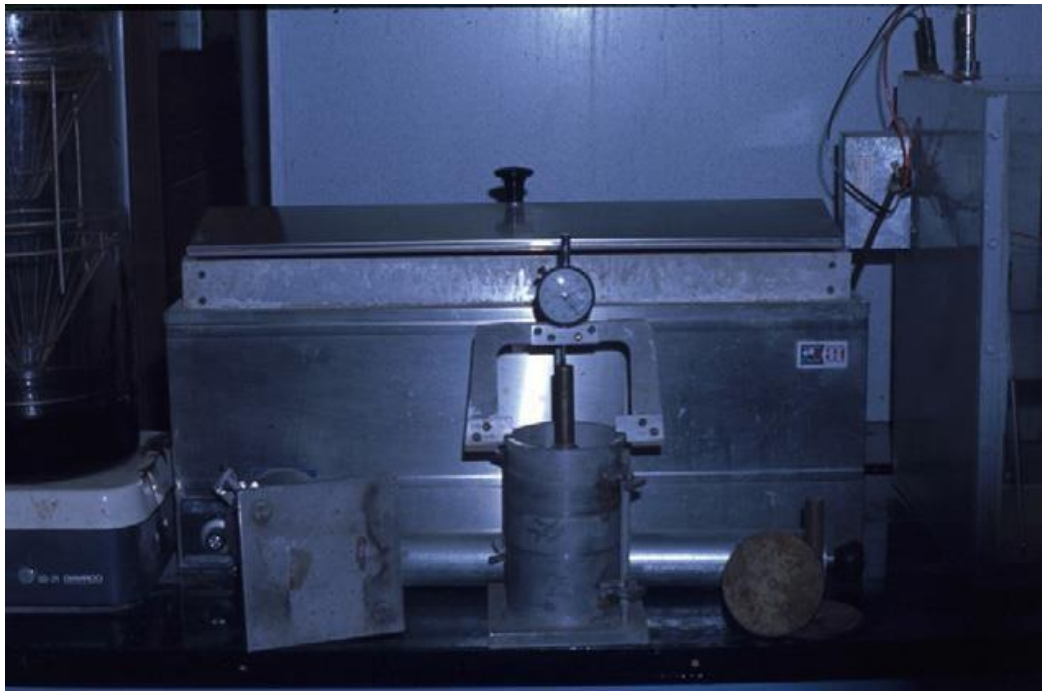


Figure 2.11 Volume expansion test apparatus ASTM D4792(Wang et al., 2010)

2.8 STABILIZATION OF STEEL SLAG AGGREGATE

Slag aggregate should be stabilized first before use in concrete due to the presence of CaO and MgO. These stabilization processes are of two types aging by stockpiling & carbonation. EAF slag was weathered in the open air and sprinkled with water atleast 90 days each day(Lam et al., 2017). Which produced a thin layer of calcite on the surface of weathered steel slag aggregates was mostly due to the interaction of CaO with CO₂ and water to generate CaCO₃. Weathered aggregate specimens were taken and washed with water to test if the calcite coating can be removed; however, the coating layer was found to be completely adhered to the surface of the aggregate and thus cannot be removed by washing.(Palankar et al., 2016).Steam and autoclave methods are used for fine steel slag aggregates to stabilize them by reducing the lime content(Lun et al., 2008).In carbonation the chamber was heated

to 70° Celsius and vacuumed to 0.03 MPa. The reactor was then filled with CO₂ until the pressure reached 0.3 MPa. The carbonation time was four hours(Pang et al., 2016). There was decrease in deleterious pores by 24.4 percent after rapid carbonation, whereas the harmless pores increased by 67.9 percent. Calcium hydroxide created spindle and rod-like columnar CaCO₃ particles as a reaction result(Pang et al., 2015). The lime diffraction patterns that were seen in the steel slag powders before carbonation vanished after carbonation. After carbonation most of the hazardous component reduced that caused expansion(Frías et al., 2010). Calcium-containing substances in the form of CaO, CaOH₂, C₂S, C₃S, or C-S can be carbonated and made stable(Mo et al., 2020). But the ageing of slag is most preferred process as compared to carbonation because carbonation is an expensive process. However, slag treatment has a significant impact on pozzolanic strength, which is raised fourfold when compared with untreated slag.

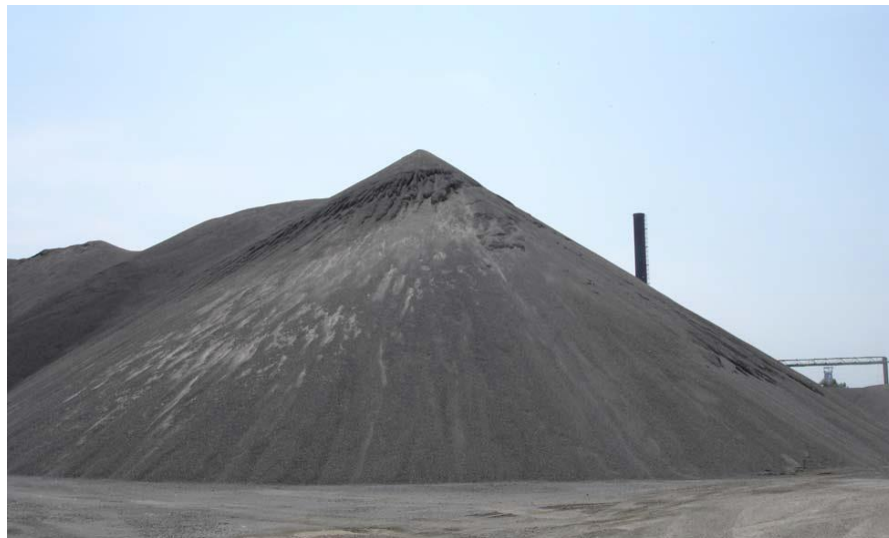


Figure 2.12 Stabilization of steel slag aggregate by Aging process(Patel, 2008)

2.9 GROUND GRANULATED BLAST FURNACE SLAG (GGBFS)

2.9.1 Production

GGBFS is a byproduct of iron blast furnaces. Blast furnaces are fed a regulated combination of iron ore, coke, and limestone and run at around 1,500 degrees Celsius (Siddique and Iqbal Khan, 2011). Molten iron and molten slag when iron ore, coke, and limestone melts in a blast furnace. Molten slag floats on top because it is lighter. Slag granulation requires the cooling of molten slag by high-pressure sprinklers. It quickly helps to cool molten slag, resulting in granular particles no bigger than 5 mm in size. Since this rapid cooling prevents the formation of larger crystals, the final granular material is composed of approximately 95%

non-crystalline calcium-aluminosilicates. GGBFS is a very fine powder made by granulated slag in revolving ball (Siddique and Iqbal Khan, 2011).

2.9.2 Physical & Chemical property of GGBFS

GGBFS is used as a replacement for cement as it has a low heat of hydration, improves durability, improves workability, reduces CO₂ emission & has environmental benefits but one disadvantage is it has later strength gain (Lee et al., 2019; Saluja et al., 2019). GGBFS is having less specific gravity and is more finer as compared to cement hence it makes the concrete more denser as it fills more voids and for hydration the amount of water required is more due high specific surface area (Saluja et al., 2019). It has both glassy and crystalline phases. Its cementitious capabilities are due to its glassy nature. The glass content of GGBFS is between 85 and 90 percent. The GGBFS is activated by alkalis and sulphates to generate its hydration products in this process. Some of them react with Portland cement products to create additional hydrates with pore-blocking properties. For the same total pore volume, the outcome is a cured cement paste with more extremely small gel holes and fewer considerably larger capillary pores because of this GGBFS concrete is less permeable and more durable (Siddique and Iqbal Khan, 2011).

Table 2.4 Physical and chemical properties of GGBFS

Elements	(Siddique and Iqbal Khan, 2011)	(Lee et al., 2019)	(Saluja et al., 2019)	(Aboutalebi Esfahani and Basij, 2019)
SiO ₂	35.34	34.2	31.6	34-40
Al ₂ O ₃	11.59	14.3	21.7	10-12
Fe ₂ O ₃	0.35	0.5	2.5	-
CaO	41.99	45.1	33.2	34-40
MgO	8.04	3.9	8	7-10
MnO	0.45	0.2	-	0.6-2
S ₂	1.18		-	1-1.55
SO ₃	0.23	0.2	0.18	-
TiO ₂	-	0.7	-	
Specific	2.95	2.92	2.83	-

Gravity				
Specific Surface (m ² /kg)	435-480	435	385	-

2.10 SOIL COMPACTION METHOD

There are 4 compaction methods Modified proctor test conforming to ASTM D1557 , Vibrating Hammer conforming to ASTM C1435, Vibrating Table conforming to ASTM C1176 & Superpave gyratory compaction test out of these 4 tests the vibrating table generates the least compaction since it utilizes the least amount of energy, but the Superpave gyratory causes the most compaction because it uses both shearing and compression force. (Şengün et al., 2019). But the most widely used test is the Modified Proctor test also called as soil compaction method(Calis and Yıldız, 2019; Harrington et al., 2010; Khoury et al., 2019; M. N.-T. Lam et al., 2018a, 2018b; Mardani-Aghabaglou and Ramyar, 2013).

Compaction curve was made in modified proctor test by compacting the mix in 5 layers at different moisture content i.e 5%,6%,7%,8% & 9% in conformance to ASTM D1557.The mix is compacted in 5 layers in 152 mm mould. Each layer is given 56 blows with the 4.75 kg rammer and the free fall is of 457 mm. The total compactive effort is of 2700 kn-m/m³. At last the dry unit weight is noted. For different moisture contents, the technique was repeated with a one-percentage increase in moisture content. From this test a relation was established between dry density & moisture content and a curve was plotted which gave the optimum moisture content(Lam et al., 2020). Similarly the test can be repeated by changing percentage of cementitious content by 1% to get the maximum dry density (Arnold et al., 2009; M. N.-T. Lam et al., 2018b). With increase in EAF slag aggregate the dry density of the concrete increased but with the replacement of the cement by flyash the density decreased & the OMC was between 6-8% (M. N.-T. Lam et al., 2018a).

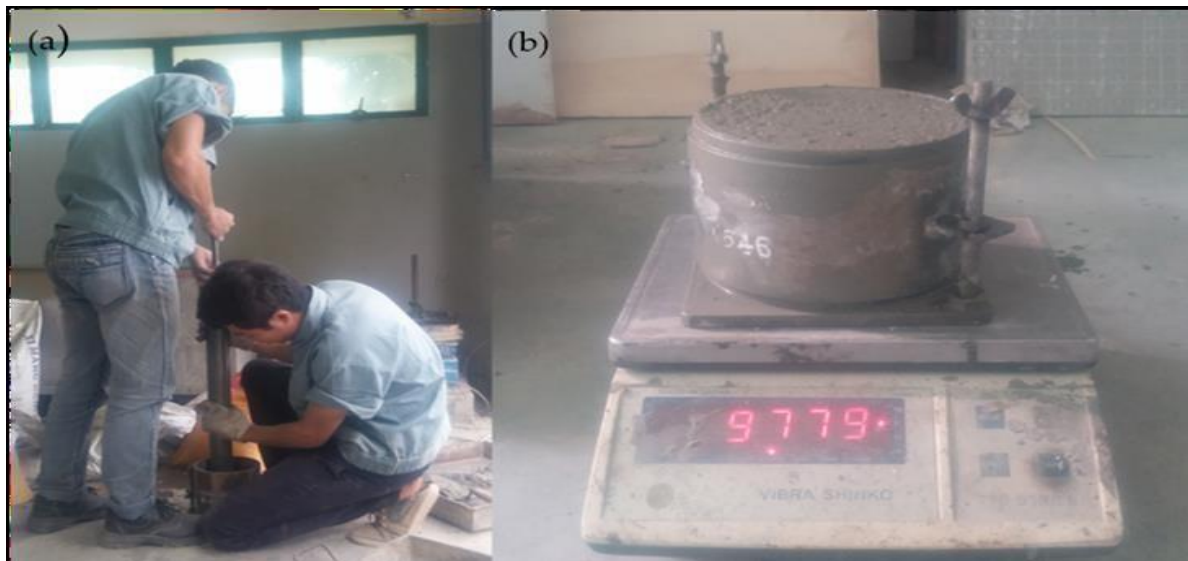


Figure 2.13 Modified Proctor Test(M. N.-T. Lam et al., 2018a)

2.11 WORKABILITY OF STEEL SLAG AGGREGATE

Modified Vebe test is done conforming to ASTM C1170. For RCC, the typical Vebe apparatus for conventional no-slump concrete has been adapted. Under a surcharge, fresh RCC is put in the 1/3 ft³ (9.4 l) cylindrical steel container. The sample is vibrated until it is completely consolidated beneath the surcharge. ASTM C 1170 provides techniques for evaluating RCC with and without a 50 lb (22.7 kg) surcharge. The vebe time increases as the angularity & fracture particle increases & hence the workability decreases, The Vebe time for waste-containing samples ranged from 42 to 60 seconds. (Tavakoli et al., 2020). The vebe times for RCC dam mixes are 10–25 seconds. The Vebe time of 30–40 s, on the other hand, has been identified as the most acceptable range for RCCP pavement and overtopping protection mixes(Rooholamini et al., 2018). With increase of slag aggregate in concrete there is decrease in workability (Etxeberria et al., 2010).The concrete made from 100 % slag aggregate had slump of 200 mm(Netinger et al., 2011).As EAF is having rough texture and high porosity then also all the mixture made using slag aggregate ,Fly ash & Silica fume was able to achieve a slump of 200 ± 20mm(Abu-Eishah et al., 2012).When slump of ground GGBFS was compared to EAF slag aggregate concrete the slump of GGBFS was more and was equivalent to convention mix(Lee et al., 2019).

2.12 MECHANICAL PROPERTIES OF CONCRETE

2.12.1 Compressive strength

In RCC the control mix strength prepared using 100 natural aggregate was more as compared to mix that was prepared using 100 % EAF slag aggregate even when compacted at different

time periods i.e. 0 min, 15 min, 30 min, 60 min, 90 min, But M40 strength was achieved using 100% EAF Slag aggregate (M. Lam et al., 2018). Using 20% of fly ash the compressive strength was improved in long term (i.e. 90 days strength) & increasing the fly ash percentage reduced the strength (M. N.-T. Lam et al., 2018b). Using slag cement & fly ash as replacement for portland cement (i.e. Portland cement 50%, slag cement 30%, fly ash 20%) also increased the strength and it was 41 MPa. In RCC the optimum amount of basic oxygen slag aggregate that can be used is 25% and the strength achieved was 41.7 MPa (Aboutalebi Esfahani and Basij, 2019). The increased global strength of concrete of the composite with EAF slag compared to the conventional ones is most likely due to a change in the quality of the cement matrix–aggregate contact surface, rather than variations in the aggregate strength properties (Pellegrino and Gaddo, 2009). Conventional concrete made up of AOD slag & EAF slag aggregate obtained almost the same strength (Adegoloye et al., 2015). The conventional alkali activated concrete made up of 100% GGBFS and 100% slag aggregate was able to achieve a strength of 51 MPa but the strength reduced with the increase in slag aggregate because the calcite coating on slag aggregate hinders the bonding with the aggregate and the paste (Palankar et al., 2016).

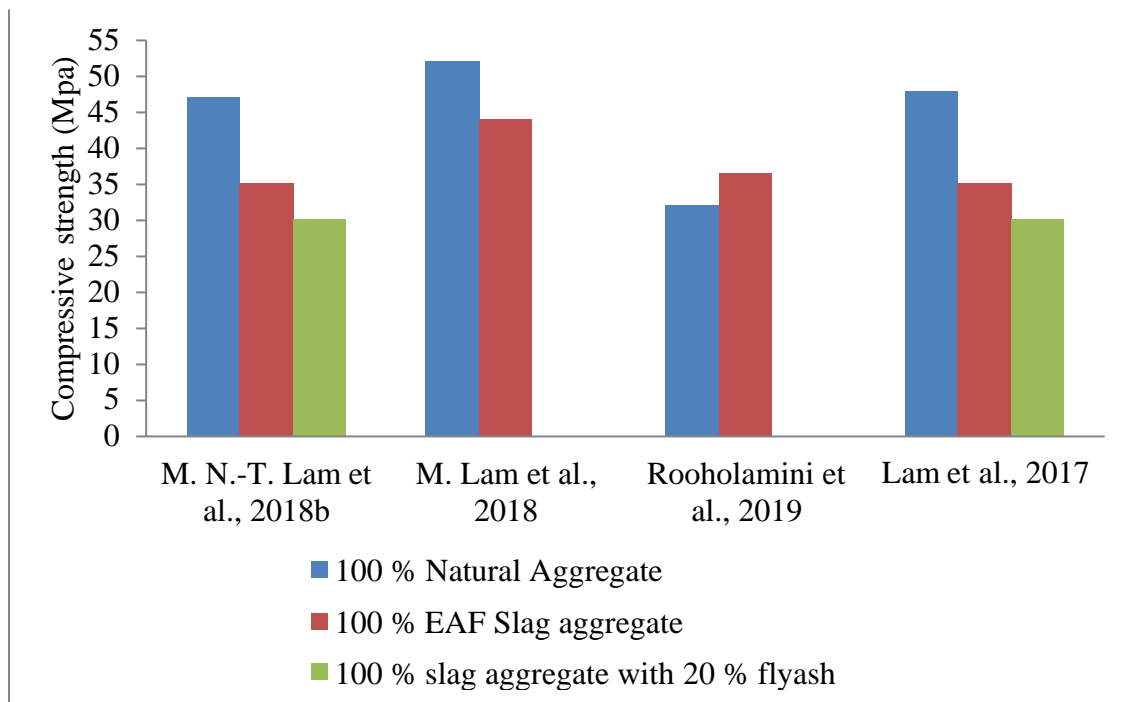


Figure 2.14 Compressive strength comparison

When steel slag is used in powder form (10-20%) in magnesium potassium phosphate cement paste it improves the early compressive strength by improving the particle size distribution and filling the voids (Yang et al., 2018). The concrete made up of 310 kg/m³ cement and w/c ratio of 0.6 with no admixture has got a strength of 35 MPa using 50% EAS

as fine aggregate replacement & 100 % slag aggregate(Manso et al., 2006).The minor increase in strength can be ascribed to the shape, size, and surface roughness of steel slag, which increases aggregate interlocking and the ITZ (Patel, 2008).BOF and LMF slag have porous ITZ as compared to EAF slag aggregate & BOF and LMF slag aggregate were having a porous outer layer which was not present in EAF slag aggregate(Brand and Roesler, 2018).

2.12.2 Split tensile strength

In RCCP the splitting tensile strength of control mix was more as compared to mix having 100 % EAF slag aggregate, But with the delay in compaction the strength of mix having 100 % slag aggregate improved due to rough texture of aggregate & the pores were filled by ettringite(M. Lam et al., 2018).When the splitting tensile strength was done on different specimen and were kept at some angle to the base of UTM machine then cylinder splitting has achieved highest strength,then diagonal-cube splitting and least strength was of side-cube splitting. In side-cube splitting specimens and cylinder splitting specimens, the strength of coarse steel slag concrete was clearly size-dependent. The size sensitivity of the side-cube splitting specimens was greater than that of the cylinder splitting specimens(Nguyen et al., 2020).In conventional concrete the failure mode was same as cube and it was seen that there was a strong bond between the cement mortar and the steel slag aggregate(Abu-Eishah et al., 2012).

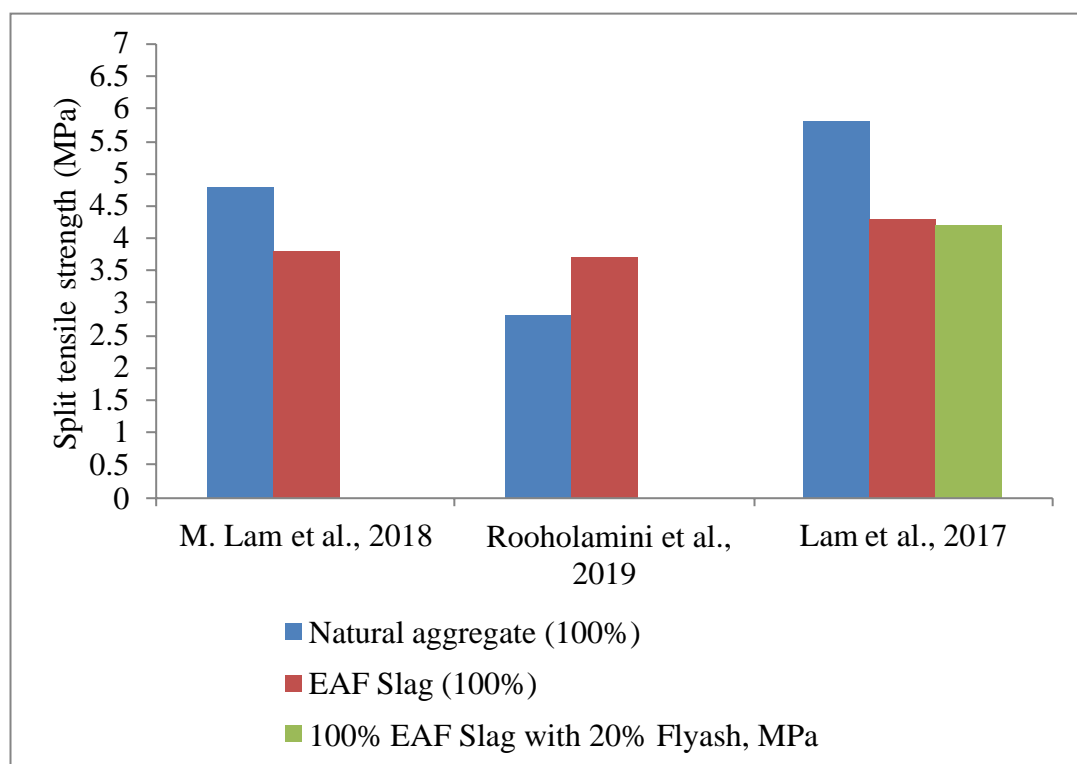


Figure 2.15 Split tensile strength comparison

Splitting took place inside the cement matrix–aggregate in the majority of cases for samples with electric arc furnace slag, showing a strong link between binder and aggregate, aided by typical surface pores and roughness of Black (Oxidizing) slag; splitting surfaces in conventional conglomerate, on the other hand, showed a plain separation between aggregates and cement matrix, most likely due to its smooth round form of natural fluvial aggregate: this has lowered the global strength(Pellegrino and Gaddo, 2009).When 40% of the aggregates were replaced by steel slag aggregates and were reinforced with HYSD bars or basalt bars with the decrease in diameter of the bar the bond stress increased(Anwar et al., 2020).

2.12.3 Flexural strength

With testing age the flexural strength rose of slag aggregate concrete, All flexural parameters at LOP increased as the compressive strength of coarse steel slag concretes increased, including load-bearing capacity, midspan deflection capacity, midspan flexural strain, and energy absorption capacity(Nguyen et al., 2020).Replacement of fine steel slag and coarse steel slag produced strength flexural strength of 9.3 MPa which was more than the reference concrete(Chunlin et al., 2011).As compared to control mix the mix having coarse steel aggregate 100% & 50% was having more flexural strength and fine steel slag aggregate was having less strength. The failure reason in coarse steel aggregate was aggregate itself and not the ITZ & in case of fine steel aggregate the failure was due to the cement paste(Rooholamini et al., 2019).

2.12.4 Elastic modulus

The delay in compaction had little effect on the elastic modulus of control mix RCCP and 100% EAF slag aggregate RCCP at 28 days of age. The range of values (30000–36000 MPa) is comparable to that of standard paving concrete. From compressive strength of samples at 28 days we can predict the elastic modulus of conventional mix RCCP and slag aggregate mix RCCP(M. Lam et al., 2018). The stress-strain curve (under traction) was used to evaluate the cylindrical samples, with the secant modulus varying between 5 and 70% of the ultimate stress. The beam specimens were tested to two methods: (a) determining the stress-strain curve (under bending stress) using the secant modulus from 5 to 70% of ultimate stress, and (b) using Mohr's analogy, which is based on mid-span deflection measured with a linearly varying differential transducer (LVDT) under a load similar to 70% of the rupture load.(Albuquerque et al., 2011). Generally the elastic modulus increases in the presence of EAFs, especially in concretes with a lower water-cement ratio(Monosi et al., 2016).The concrete mixes designed for different strength showed almost same modulus of elasticity as

elastic modulus is dependent on the density of concrete & concrete incorporating steel slag has high unit weight and hence more modulus of elasticity(Papayianni and Anastasiou, 2011).

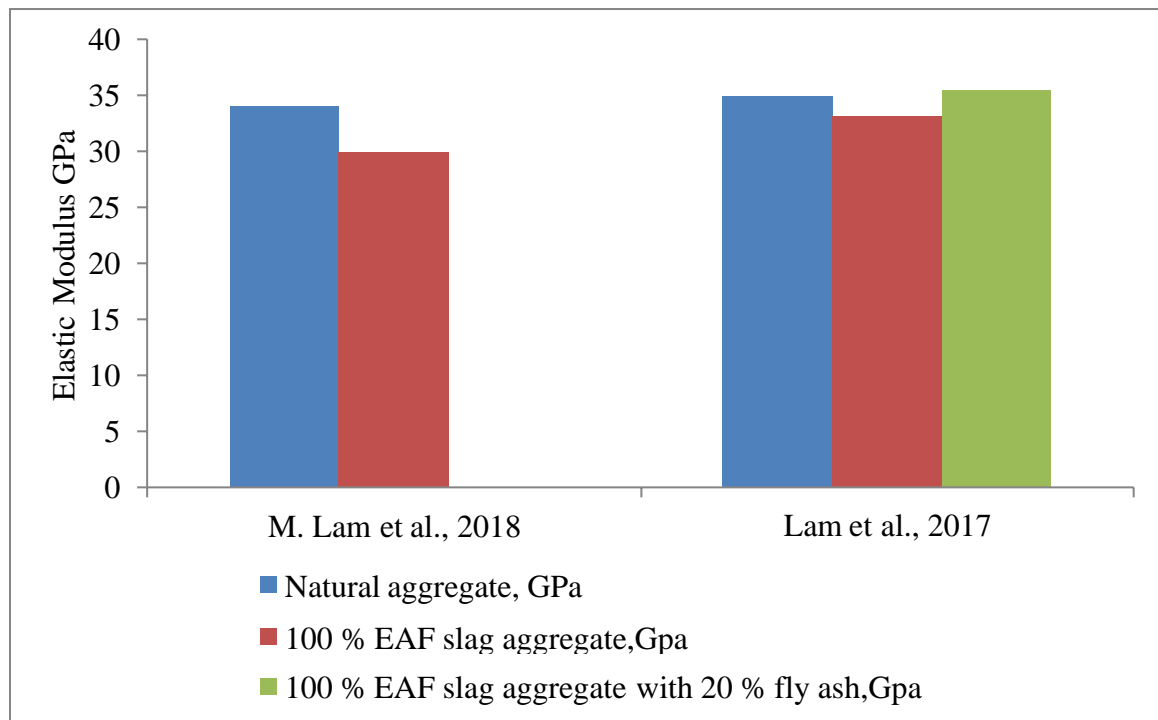


Figure 2.16 Elastic Modulus Comparison

2.13 DURABILITY PROPERTIES OF CONCRETE

2.13.1 Water absorption

The water penetration test was done as per BS EN-12390-8:2000 is used to evaluate the permeability of concrete(Sekaran et al., 2015). Conventional RCCP mix was having 4.31 % water absorption but with replacement by 50 % & 100% EAF slag aggregate it was 4.88% & 5.36% i.e. 13% & 24 % growth also 40 % flyash content increase the water absorption (M. N.-T. Lam et al., 2018b). With the decrease in the grading size of aggregate, the water penetration depth increases as the distance between adjacent EAF slag particles grows, as does the overall extent of the interfacial transition zone(González-Ortega et al., 2019; Palankar et al., 2016). The water absorption capillarity study shows that the fiber-reinforced CEAFS has generally good qualities and can withstand aggressive environments.Slightly poorer properties were shown by unreinforced CEAFS, implying a lower level of environmental resistance(Ortega-López et al., 2018). Steel slag aggregate high strength concrete was having water porosity between 12.1 to 12.4 % after 28 days which was due to the high porosity in slag aggregate (Adegoloye et al., 2015).

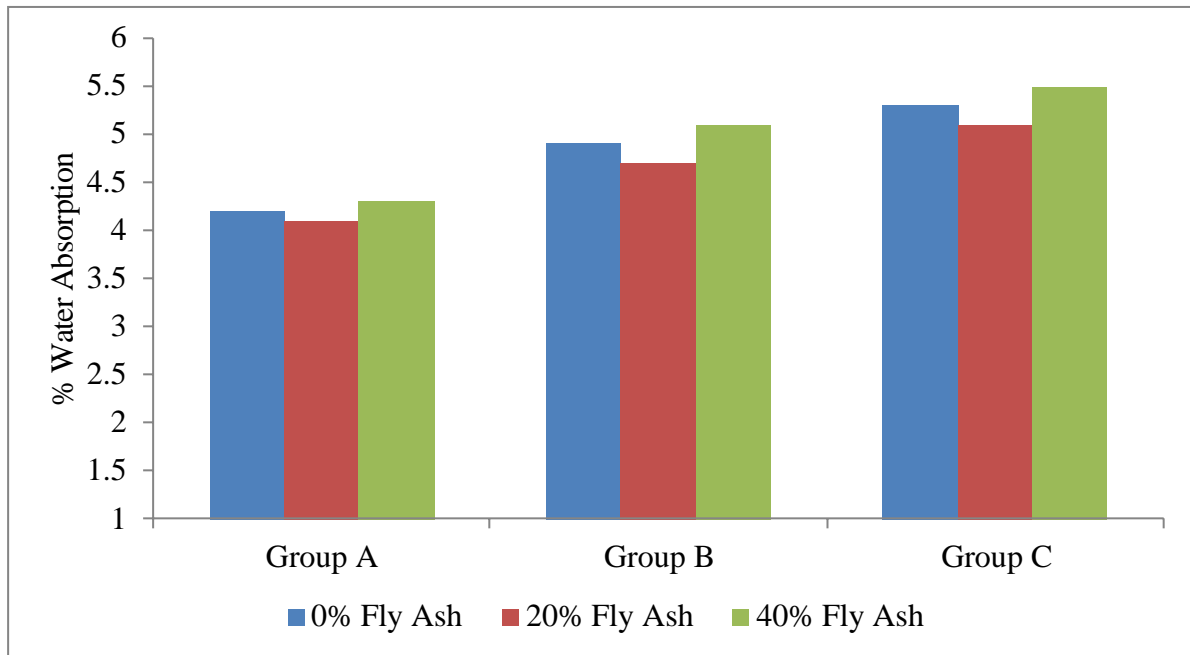


Figure 2.17 Total water absorption values of RCCP at 91-day age (M. N.-T. Lam et al., 2018b)

2.13.2 Wetting and Drying Cycle

The combined effects of thermal dilation and contraction, as well as shrinkage due to humidity variations, cause damage in this test. The curing of three specimen of each mixture was done for 28 days and they were subjected to 30 cycles of alternate wetting and drying with immersion time 16 hours and drying time 8 hours at 110°C (Manso et al., 2006). The hydration reaction causes the material to expand, whereas ion mobility can cause stains on the material's surface, which has a negative aesthetic impact. At the end of each cycle's drying period to identify the no. of stain points and wear a visual inspection is performed and they are recorded. A mechanical extensometer was used to measure the dimensional variation on a slab shaped specimen by taking the relative distance between the 4 reference points (González-Ortega et al., 2019). There is a increase in stain points in slag aggregate concrete as compared to conventional concrete & the dimensional stability of slag aggregate concrete towards expansion is slightly more as compared to conventional concrete (González-Ortega et al., 2019). The mix with metallic fibers were having lower strength loss and with synthetic fibers had higher strength loss (Ortega-López et al., 2018).

2.13.3 Carbonation

The carbonation depth of conventional concrete was less than 1 mm whereas for slag aggregate concrete was 6 times more. Mixes with a higher superplasticizer content had 44 percent higher carbonation depths than equivalent mixes with a lower superplasticizer content. The higher the humidity and rain exposure, the lower the average CO₂ diffusion coefficient and, as a result, lower the penetration depth (González-Ortega et al., 2019). Slag

aggregate concrete with fibers were having higher resistance to carbonation as compared to concrete without fiber(Ortega-López et al., 2018).

2.13.4 Abrasion resistance

Abrasion resistance was found out using wide wheel abrasion test, the mix having 100% slag aggregate was having the highest resistance to abrasion as compared to conventional RCCP mix this was due to rough texture of slag aggregate and mix having 20 % fly ash showed good resistance as compared to mix having 40 % fly ash(M. N.-T. Lam et al., 2018b).By other authors the abrasion resistance was done as per ASTM C779 and it was found that the EAF slag aggregate concrete showed 50 % less wear compared to nominal mix since it is having good mechanical properties(Papayianni and Anastasiou, 2011).Since the abrasion resistance of steel slag aggregate is more hence the overall abrasion resistance of concrete is good(Papayianni and Anastasiou, 2011).

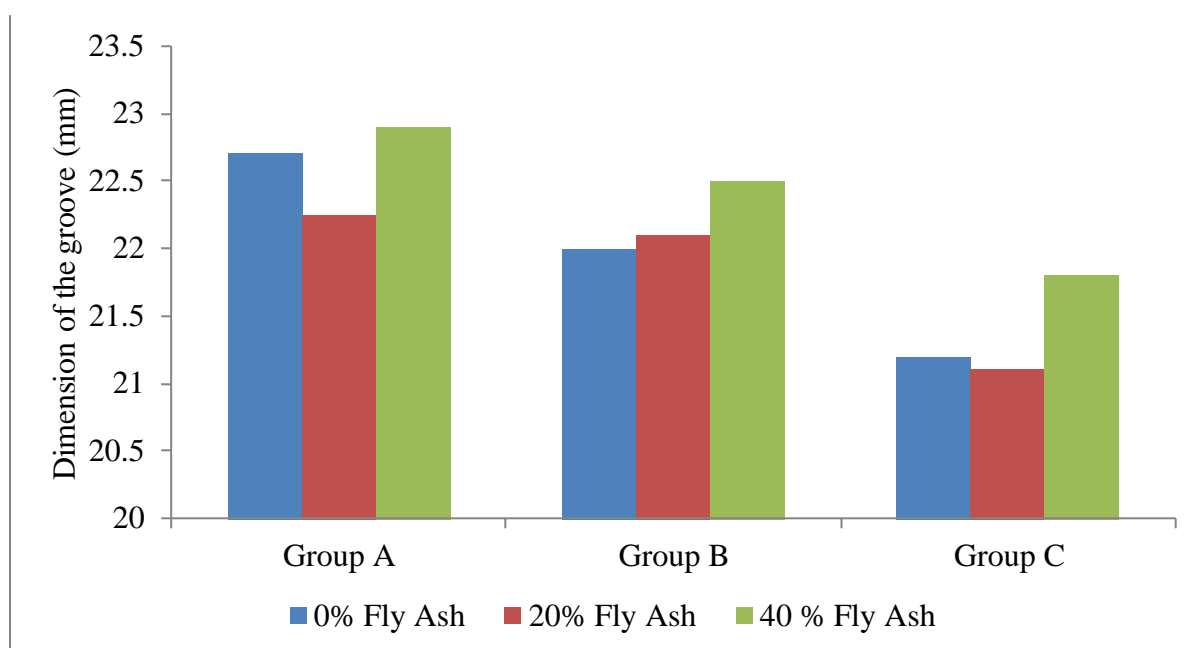


Figure 2.18 Abrasion Resistance (M. N.-T. Lam et al., 2018b)

2.13.5 Sulfate resistance

100 mm cubes are used and they are immersed in sulphuric acid solution having pH=1 as per ASTM C1012(Ortega-López et al., 2018). There was an increase in mass of the conventional as well as slag aggregate RCCP mix when fly ash was not added this was because pores of the samples were filled up by the gypsum and ettringite due sulphate reaction(M. N.-T. Lam et al., 2018b; Sekaran et al., 2015).In case of flyash mix the mass changing has reduced due reaction of flyash with portlandite to produce calcium silicate hydrate and hence reducing ettringite and gypsum formation(M. N.-T. Lam et al., 2018b). Steel slag aggregates strength loss may be attributed to softening and deterioration caused by calcium leaching out of the

aggregates. Reaction of steel slag aggregate with sulphuric acid caused pop out of the concrete surface and decreased the strength of concrete because a expansive paste was formed which exerted internal pressure on the concrete. Apart from forming expansive products, the steel slag aggregates deteriorated and softened/corroded when exposed to sulphuric acid(Devi and Gnanavel, 2014; Palankar et al., 2016).The mix that was reinforced using fibers were less prone to deterioration; the fiber reinforced concrete improved the durability of concrete(Ortega-López et al., 2018). Mix made up of steel slag aggregate expanded more as compared to concrete made of silica calcareous aggregate when seen after 1 year, the expansion of concrete of EAF slag aggregate was 0.017 , In stabilized slag aggregate was 0.026 & in silicocalcareous aggregates was 0.008(Adegoloye et al., 2015).

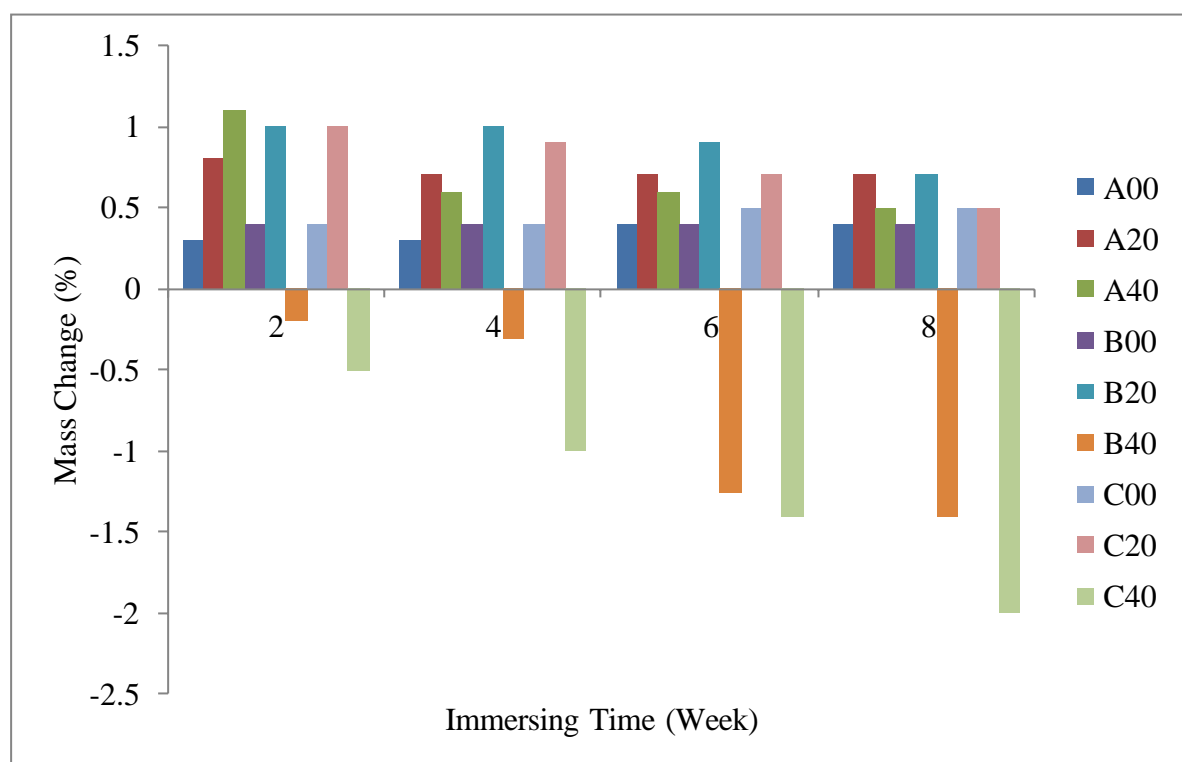


Figure 2.19 Sulfate Resistance (M. N.-T. Lam et al., 2018b)

2.13.6 Alkali silica resistance

The accelerated mortar bar method and concrete prism are used to check the length change due to alkali-silica reaction as per ASTM C1260 & ASTM C1293. The 14-day expansion value of mortar bar made with EAF slag aggregate was 0.036 percent due to alkali-silica reaction which indicates that the EAF slag aggregate is least reactive due to absence of SiO_2 . The presence of portlandite, according to the XRD analysis is a major cause of this expansion. Furthermore, fly ash reduced the expansion of the slag-mortar bar due to pozzolanic reactions(M. N.-T. Lam et al., 2018b). Silicates present in slag is stable but slag contains a significant amount of glassy phase which causes the reaction with alkalis in

cement. Since EAF slag is having variable chemical and microstructural properties hence they have a reactive nature with alkalis (Manso et al., 2006).

2.13.7 Autoclave Testing

This test is done as per ASTM D4792. In comparison to the control mixture, there was an increase in expansion in concrete when natural aggregate was substituted with slag aggregate; an increase in 50% EAF slag aggregate mix was 13%, and an increase in 100% EAF slag aggregate was 50%. During the hydration reaction in autoclave most of the specimens were not broken hence it can be said that by leaving EAF slag aggregate in the open atmospheric condition it can be stabilised and used as a replacement of natural aggregate in RCCP mix (M. N.-T. Lam et al., 2018b). The specimen with 100 percent steel slag aggregates shrank by 0.166 percent on average (Patel, 2008). With the addition of fibres the EAF slag aggregate mix resulted in slightly lower shrinkage than non-reinforced mixtures (Ortega-López et al., 2018).

2.13.8 Carbonation

The carbonation depth of conventional concrete was less than 1 mm whereas for slag aggregate concrete was 6 times more. Mixes with a higher superplasticizer content had 44 percent higher carbonation depths than equivalent mixes with a lower superplasticizer content. The higher the humidity and rain exposure, the lower the average CO₂ diffusion coefficient and, as a result, lower the penetration depth (González-Ortega et al., 2019). Slag aggregate concrete with fibers were having higher resistance to carbonation as compared to concrete without fiber (Ortega-López et al., 2018).

2.13.9 Rapid Chloride Permeability Test

In RCPT test the flow of current is measured through the specimen, but there will be an increase in conductivity since the Fe content in EAF slag aggregate is more. Hence RCPT will not give exact value of chloride permeability. Ionic diffusion tests will have more appropriate results as compared to RCPT (Abu-Eishah et al., 2012). Concrete incorporating EAF slag aggregate and fly ash is less permeable for chloride ion as compared to conventional concrete (Sekaran et al., 2015). 30 % coarse aggregate replacement, on the other hand, falls under moderate penetrability. 40 % FA replacement outperforms 30 % CA replacement (Devi and Gnanavel, 2014).

2.13.10 Freeze and thaw test

The test is done as per ASTM C666 (Khoury et al., 2019). The slag aggregate concrete showed the same results as conventional concrete there were no signs of scaling and cracks

on concrete(González-Ortega et al., 2019). The air entraining agent caused large amount of porosity resulted in substantial tolerance to freezing conditions and a reduction in the thermal/expansive stress(Manso et al., 2006; Pellegrino and Gaddo, 2009).Conventional concrete made up of fifty percent fine slag aggregate and hundred percent coarse slag aggregate had more compressive strength as compared to other mixes and low water penetration was there hence the damage was less(Manso et al., 2006).

2.14 CONCLUSION

A review is made in this paper regarding the mechanical & durability properties of concrete pavement that is effected by addition of steel slag aggregate.

- i. On the basis of physical and chemical properties of EAF slag aggregate it can be said it has less expansive properties as compared to other slag aggregate.
- ii. EAF slag aggregate have good microstructure as compared to BOF and LDF slag aggregate.
- iii. EAF slag aggregate can be used in concrete after volume stabilization by stockpiling or carbonation.
- iv. Even EAF slag is having more porosity and rough texture then also a workable mix can be achieved.
- v. As the unit weight of slag aggregate is more as compared to natural aggregate hence they produce a good abrasion resistance concrete.
- vi. The conventional concrete incorporating EAF slag aggregate and RCC incorporating EAF slag aggregate achieves the mechanical strength which is comparable to nominal mix concrete.
- vii. EAF slag aggregate concrete made using partial replacement of cement using different SCM produces more strength as compared to reference concrete because the pores of slag aggregate is filled due to the pozzolanic reaction.
- viii. The durability properties of concrete is affected when natural aggregate is replaced by slag aggregate due to its chemical composition(i.e. free lime & free magnesium oxide).
- ix. The durability can be improved with addition of Fly ash, GGBFS or silica fume as chemicals causing volumetric expansion will be utilized.

2.15 IDENTIFICATION OF RESEARCH GAPS

Based on the above literature review, following research gaps have been identified from the present state of art:

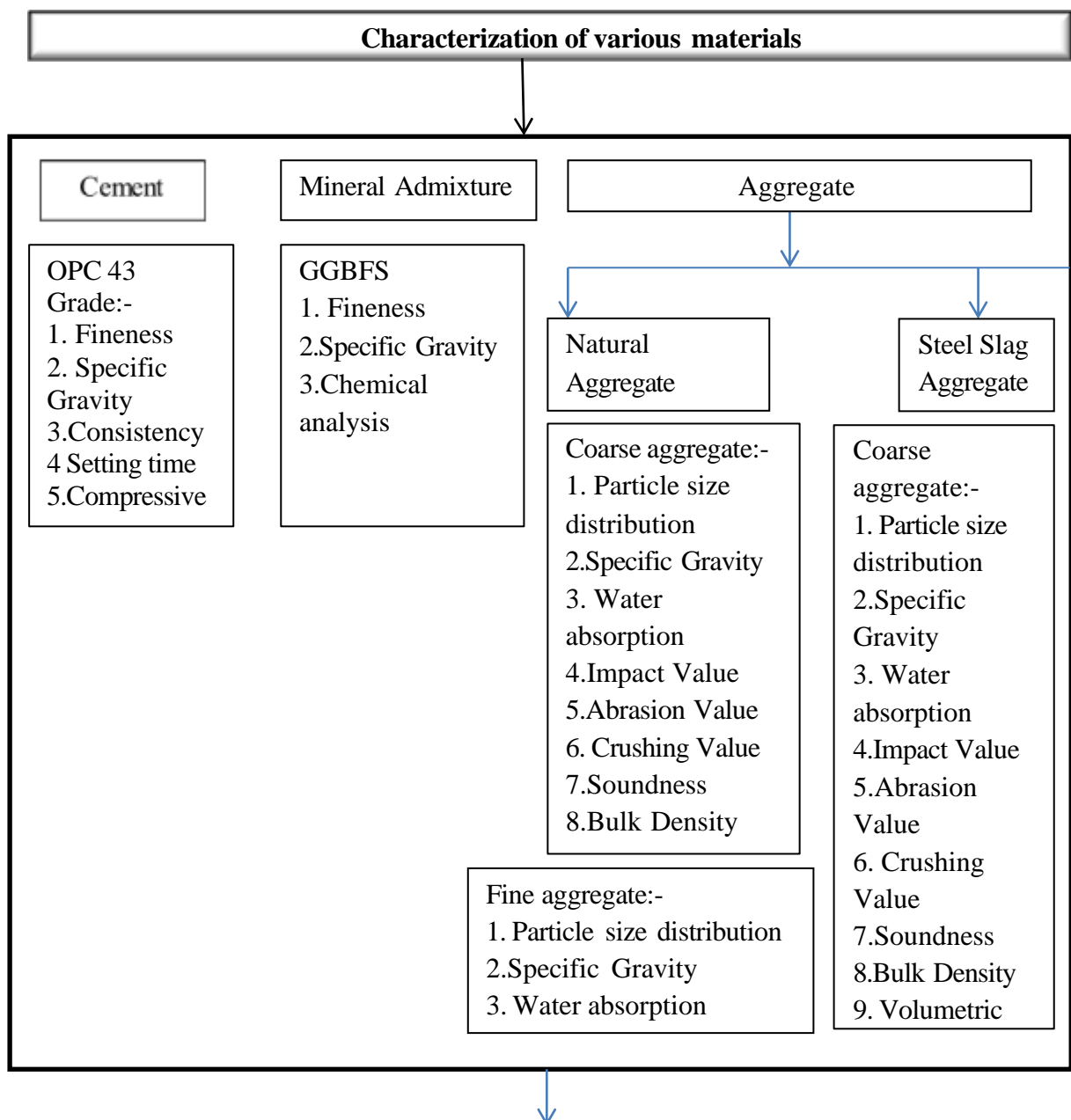
- i. No research study has been carried out on RCCP using coarse EAF slag aggregate and GGBFS.
- ii. No research study has been carried out on high volume GGBFS RCCP using EAF slag aggregate.
- iii. No research study has been carried out regarding RCCP using fine EAF slag aggregate and Fly ash.
- iv. No detailed study has been carried out regarding workability of RCCP using EAF slag aggregate and Fly ash.
- v. No detailed study regarding mechanical strength properties (i.e. flexural strength , rebound hammer) and time dependent durability properties of roller compacted concrete pavement using EAF slag aggregate and Fly ash .
- vi. Very limited study or less study or research is there regarding mechanical strength properties and durability properties of roller compacted concrete pavement using coarse EAF slag aggregate and Fly ash.

CHAPTER 3

CHARACTERIZATION OF CONSTITUENT MATERIAL, MIX PROPORTIONING AND CASTING OF SPECIMEN

3.1 INTRODUCTION

The experimental work was carried out for the research study to achieve the objectives stated in chapter 1 which includes characterization of constituent material, combined gradation, modified proctor test to determine the omc for different mixes , proportioning of the different mixes & casting of specimen for mechanical strength & durability tests. Figure 3.1 represents the outline of experimental program presented in this chapter.



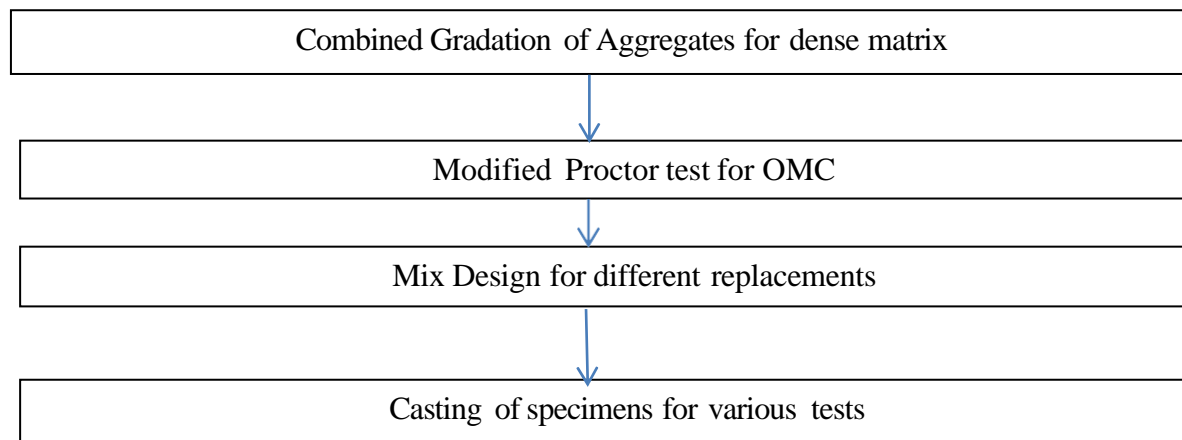


Figure 3.1 Outline of experimental study for chapter 3

3.2 CHARACTERIZATION OF CONSTITUENT MATERIAL

The various material used RCCP were Cement, Natural aggregate, coarse EAF slag aggregate, GGBFS, water. These materials were tested and their properties were determined. After knowing the properties of these material they were stored separately as per IS 4082 and same batch was used for casting.

3.2.1 Cement

OPC 43 grade of cement of brand Birla-Uttam conforming to IS 269:2015 was used for the research study. The physical properties of cement that were tested are mentioned in following sections.

3.2.1.1 Fineness

The fineness of cement was done conforming to IS 4031 Part 1(1996). Dry sieve analysis was done using 90 μm sieve and the weight retained was noted which was less than 10 % conforming to IS 4031 part 1.

3.2.1.2 Consistency

The cement consistency test was done conforming to IS 4031 Part IV(BIS 1988a) using vicats apparatus. The standard consistency of the cement was found out to be 29% .

3.2.1.3 Setting Time

The initial and final setting time of cement were determined conforming to IS 4031 Part 5 (BIS 1988b). The initial setting time was determined using needle C of vicats apparatus and

Needle F of vicats apparatus was used to determine the final setting time. The initial and final setting time were:

Initial setting time: 181 minutes

Final Setting time: 403 minutes

The setting time of cement was conforming to IS 269 (BIS 2015a), which states that IST should not be less than 30 minutes and FST should not be more than 600 minutes.

3.2.1.4 Density

The Density of cement was determined conforming to IS 4031 Part 11 (BIS 1988). The test was done using Le – Chatelier flask and the cement used to displace the volume of kerosene was noted. The density of cement was found out to be 3.14 g/cm^3 which was used further in the study.

3.2.1.5 Compressive Strength

The compressive strength of cement was found at 3, 7 & 28 days conforming to IS 4031 Part VI (BIS 1988c) and the results are shown in Figure 3.2. These results conform to IS 269 (BIS 2015a).

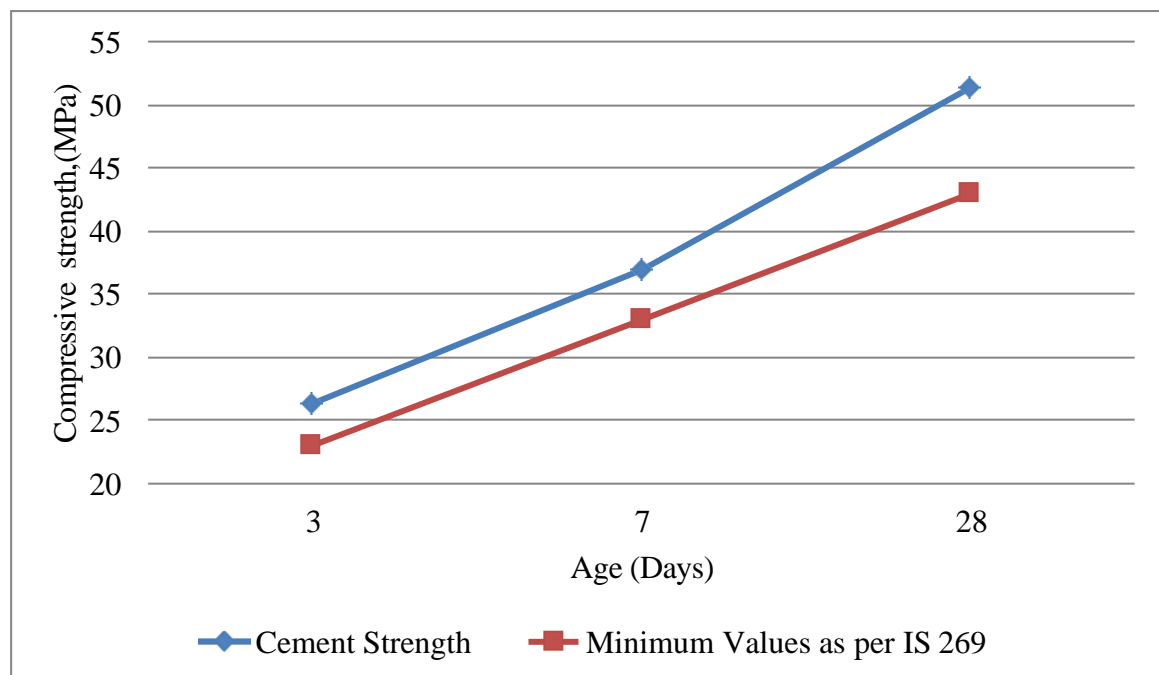


Figure 3.2 Compressive strength of cement

3.2.2 GGBFS

The GGBFS used was of JSW brand and chemical properties are mentioned in Table 3.1. The salient properties of GGBFS are mentioned in further section.

3.2.2.1 Fineness

The fineness test was done conforming to IS 1727 (1967). Wet sieve analysis was done using 45µm sieve and the residue weight was noted. The percentage weight retained was 4.1 % which was in accordance with IS 16714(2018).

3.2.2.2 Specific Gravity

The Specific gravity test was done conforming to IS 1727 (1967). The test was done using Le – Chatelier flask and the GGBFS used to displace the volume of kerosene was noted. The specific gravity of GGBFS was found out to be 2.88 which was in the range and was used further in the study.

3.2.2.3 Chemical Property

The chemical property of GGBFS are mentioned in Table 3.1 and was tested as per IS 4032 (1985) and the values were conforming to IS 12089 (1987).

Table 3.1 Chemical Property of GGBFS

GOI %	CaO %	SiO ₂ %	Al ₂ O ₃ %	Fe ₂ O ₃ %	MgO %	MnO %	CL %	IR %	SO ₃ %	Sulphide Sulphur %
-0.35	37.63	34.81	17.92	0.66	7.80	0.21	0.004	0.19	0.2	0.51

3.2.3 Natural Fine Aggregate

Fine aggregate used in the study was procured from Badarpur, New Delhi. Two different types of fine aggregate were used i.e of different zone. The different properties of both the sands were tested which were required for mix design and are mention below:



Figure 3.3 (a) Zone I sand (b) Zone III sand

3.2.3.1 Particle Size Distribution

The particle size distribution was done conforming to IS 383:2016 .Two different zone of fine aggregate were used i.e. Zone I & Zone III to get a best gradation curve and the curves are represented in Figure 3.4 (Zone I)& Figure 3.5(Zone III) .The Fineness modulus was 2.95 for Zone I sand and 2.10 for Zone III sand. Both zone of sands were within the upper limit and lower limit.

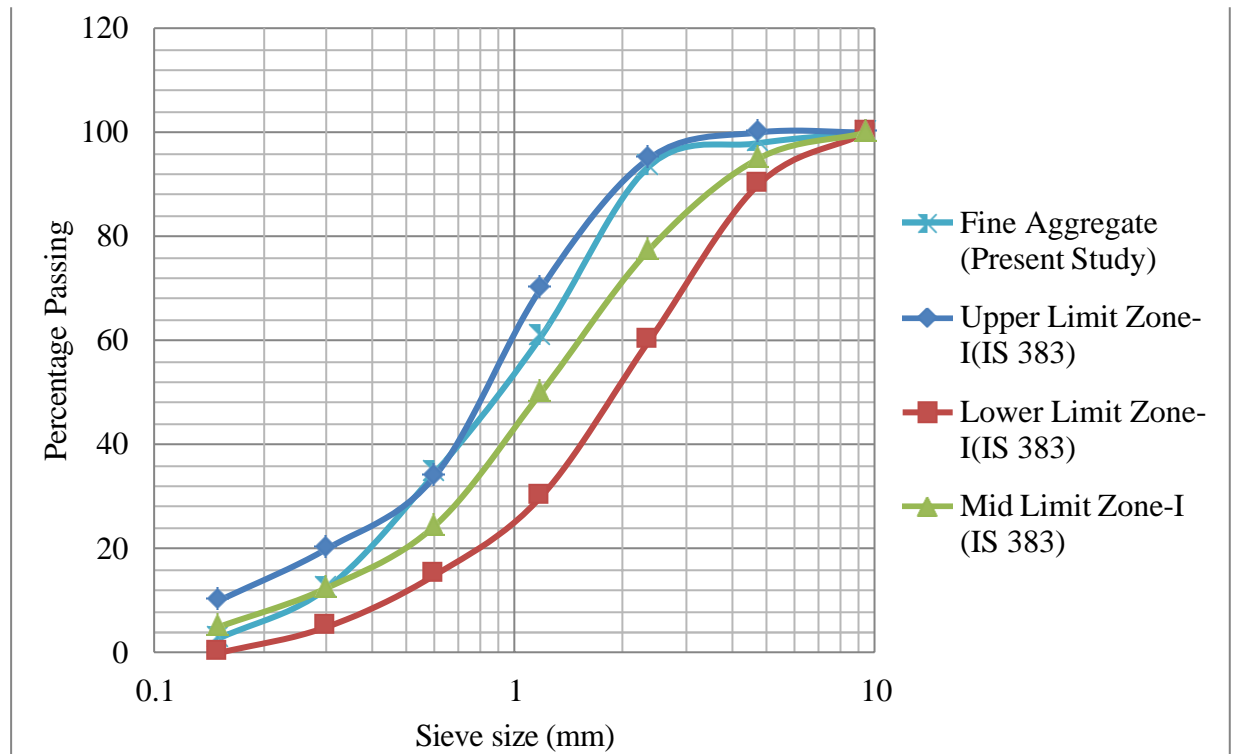


Figure 3.4 Zone I sand particle size distribution

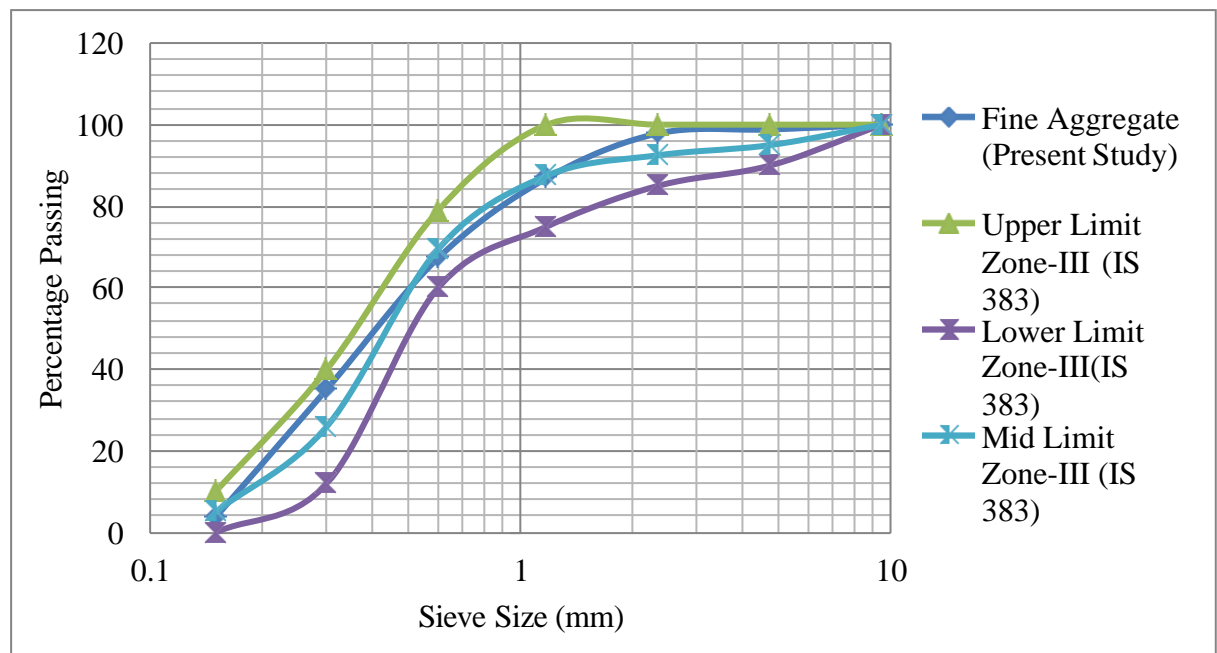


Figure 3.5 Zone III Sand particle size distribution

3.2.3.2 Specific Gravity and Water Absorption

The water absorption & specific gravity test was done conforming to IS 2386 Part III (BIS 1963b) using Pycnometer. The water absorption and specific gravity for Zone I sand is 1.18 % and 2.53 respectively. The water absorption and specific gravity for Zone III sand is 1.58 % and 2.42 respectively.

3.2.3.3 Silt Content

The silt content test was done conforming to IS 2386 Part I (BIS 1963a). For Zone I sand & Zone III sand it was 11.5 & 13.8 % respectively, Which was less than the stated limit of 15% by IS 383.

3.2.3.4 Bulk Density & Voids

The bulk density & voids test was done conforming to IS 2386 Part III (BIS 1963). For Zone I sand the bulk density in dense state, loose state and the voids in dense state and loose state were 1.60 g/cm³, 1.45 g/cm³, 37.25% & 43.13% respectively. For Zone III sand the bulk density in dense state, loose state and the voids in dense state and loose state were 1.69 g/cm³, 1.50 g/cm³, 30.16% & 38.01% respectively.

3.2.4 Natural & EAF coarse aggregate

Natural aggregate of 20 mm and 10 mm were used and were procured from local region of delhi. The EAF slag aggregates used were of two different sizes 20 mm and 10 mm that were procured from JSW Dolbi, Maharashtra plant. The EAF slag aggregates were aged for more than 2 years by stockpiling to stabilize them. The various test done on coarse aggregates are mentioned below:

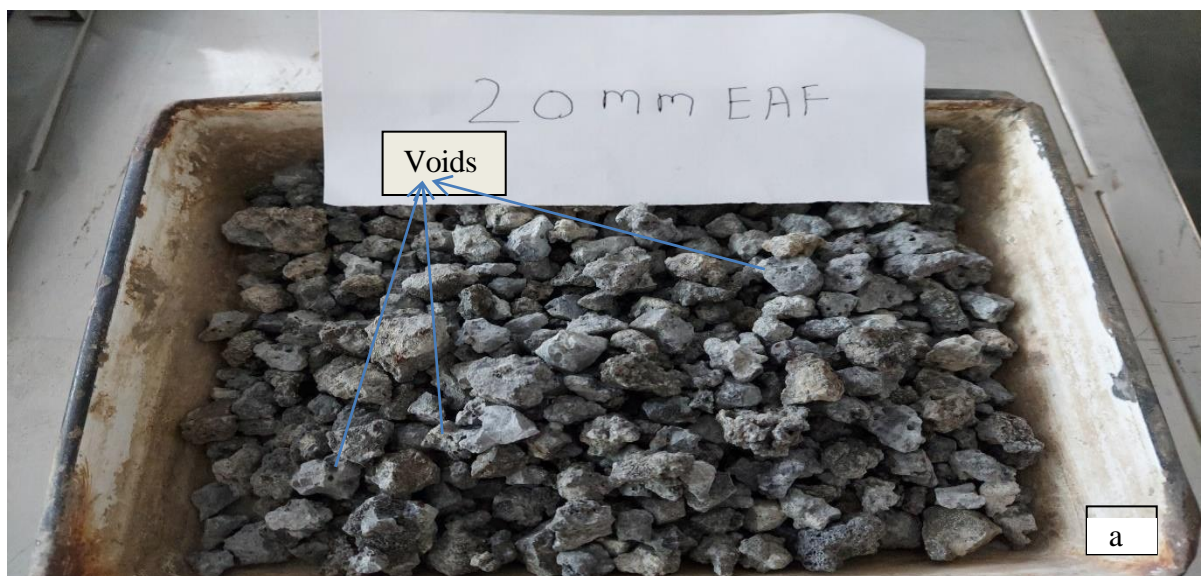




Figure 3.6 (a) 20mm EAF slag aggregate after stabilization (b) 10mm EAF slag aggregate after stabilization

3.2.4.1 Particle Size Distribution

The particle size distribution of coarse aggregate was done conforming to IS 383(BIS 2016). The results of natural aggregate are represented in Figure 3.7 & Figure 3.8. The results of EAF slag aggregate are represented in Figure 3.9 & Figure 3.10. The natural 10 mm and 20 mm are within the limit stated as per IS 383:2016. The EAF slag aggregate of 20 mm is within the limit stated as per IS 383:2016. As the 10mm aggregate are smaller in size as compared to 20mm aggregate so the calcite layer formed on the surface of it is having weaker bond and hence during crushing the calcite layer is getting removed making aggregates more finer. Hence 10mm aggregate is not within the limits.

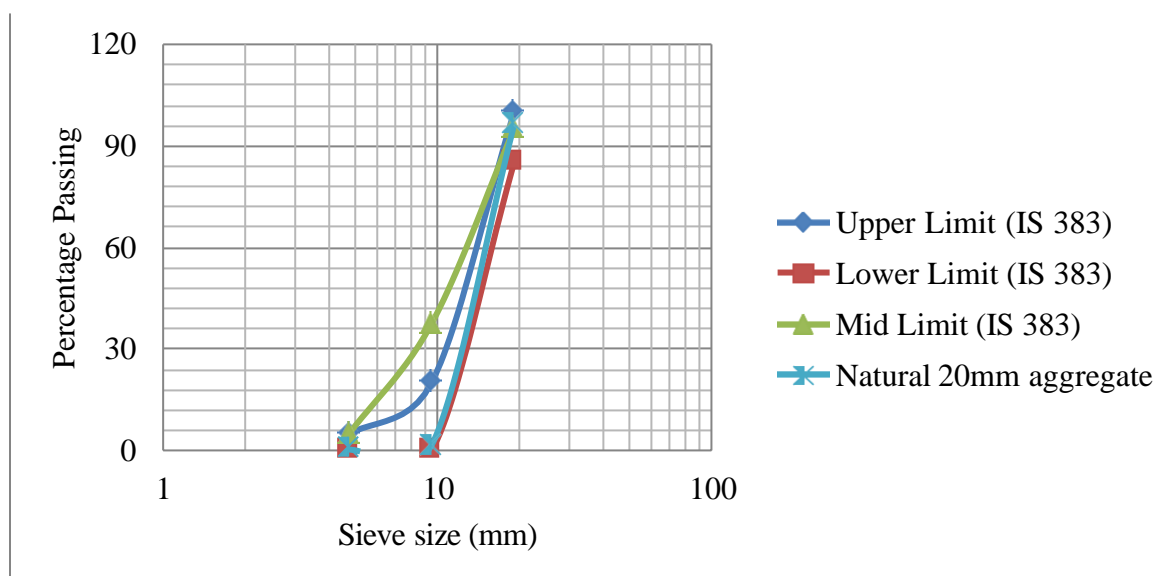


Figure 3.7 Natural 20mm aggregate particle size distribution

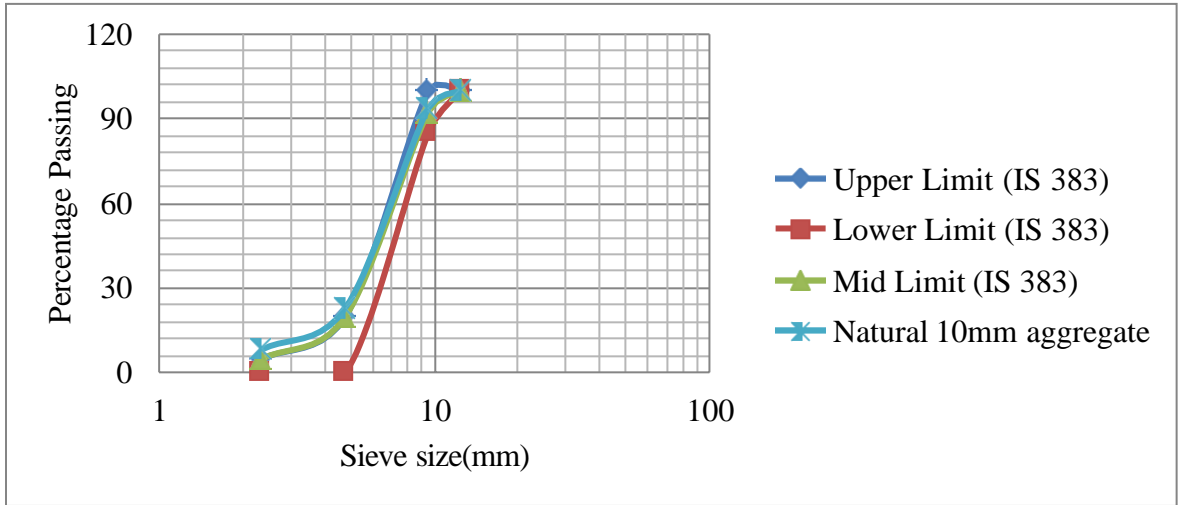


Figure 3.8 Natural 10mm aggregate particle size distribution

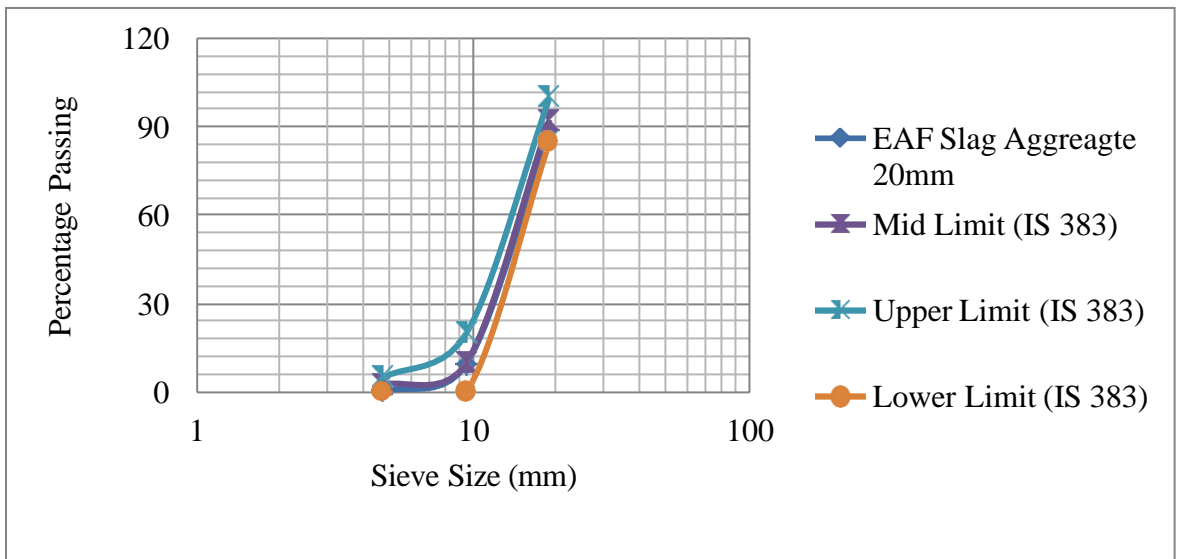


Figure 3.9 EAF slag 20mm aggregate particle size distribution

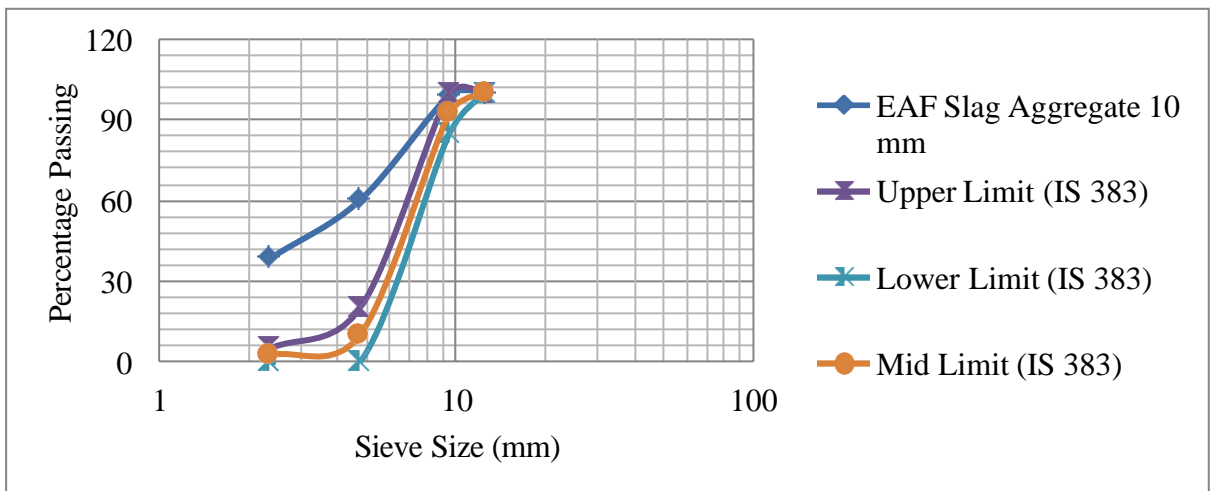


Figure 3.10 EAF slag 10mm aggregate particle size distribution

3.2.4.2 Water Absorption and Specific Gravity

The test was done conforming to IS 2386 Part III. The specific gravity was found out using wire mesh bucket and the weight was noted in air and water after that the aggregate were kept in oven to get oven dry weight. The results used in the study are mention in table. The specific gravity of EAF aggregate was more as compared to natural aggregate because of presence of Ferrous oxide making it more denser and water absorption was more of slag aggregates as they have vesicular surface structure they are more porous. All the results are within the limits conforming to IS 383 (2016).

Table 3.2 Specific Gravity and Water absorption of coarse aggregate

Type of Aggregate	Specific Gravity	Water Absorption (%)
Natural – 20 mm	2.80	0.28
Natural – 10 mm	2.84	0.24
EAF – 10 mm	3.35	1.79
EAF – 20 mm	3.37	1.15

3.2.4.3 Bulk Density & Voids

The bulk density & voids test was done conforming to IS 2386 Part III (BIS 1963).The bulk density in dense state, loose state and the voids in dense state and loose state of coarse aggregate are presented in table. As slag aggregate are having good particle size distribution and more unit weight due presence of Ferrous oxide hence they having more bulk density.

Table 3.3 Bulk density and void content of coarse aggregate

Type of Aggregate	Bulk Density (Dense State)(g/cm ³)	Bulk Density (Loose State) (g/cm ³)	Voids (Dense State) (%)	Voids (Loose State) (%)
Natural – 20 mm	1.67	1.57	40.35	43.92
Natural – 10 mm	1.71	1.55	39.78	45.42
EAF – 10 mm	1.97	1.86	41.19	44.47
EAF – 20 mm	1.84	1.66	45.40	50.74

3.2.4.4 Crushing Value

The crushing value test was performed for coarse aggregate conforming to IS 2386 Part IV (1963).The crushing value of natural aggregate was 24.36%. The crushing value of EAF slag aggregate was 18.83%. As the density is more of EAF slag aggregate hence it having good crushing value as compared to natural aggregates. But for both the coarse aggregates the values were within the limits conforming to IS 383 (2016),i.e. 30 % for wearing surface.

3.2.4.5 Impact Value

The impact value test was performed for coarse aggregate conforming to IS 2386 Part IV (1963). The impact value of natural aggregate was 13.51%. The impact value of EAF slag aggregate was 8.64%. For both the coarse aggregates the values were within the limits conforming to IS 383 (2016), i.e. 30 % for wearing surface & 45 % for other than wearing surface.

3.2.4.5 Abrasion Value

The Abrasion value test was performed for coarse aggregate conforming to IS 2386 Part IV (1963) using Los Angeles Machine. The abrasion value of natural aggregate was 22.72%. The abrasion value of EAF slag aggregate was 11.74%. For both the coarse aggregates the values were within the limits conforming to IS 383 (2016), i.e. 30 % for wearing surface & 50 % for other than wearing surface.

3.2.4.6 Soundness

The Soundness test was performed for EAF slag aggregate conforming to IS 2386 Part IV (1963). The loss in weight is 1.74 % in Sodium Sulphate solution which is within the limits specified in IS 383 (2016), i.e. 12 % .

Hence the overall physical properties of EAF slag aggregate is good and comparable to natural aggregates expect EAF slag aggregate is having higher water absorption but it is also within the limits specified in IS 383 (2016).

3.2.5 Volumetric Expansion

The volumetric expansion in EAF slag aggregate was measured conforming to EN 1744-1 by steam exposure testing device as shown in Figure 3.11 as done by (Akbarnejad et al., 2012; Fronek, n.d.) and the sample was prepared as per EN 1744-1. The average volumetric expansion was 0.411 % . The results is within the limit conforming to (Akbarnejad et al., 2012; Kumar et al., 2017) i.e. less than 1.5% for use as construction aggregate.



Figure 3.11 Steam exposure device

3.3 GRADATION FOR MIX DESIGN

The mix gradation of natural aggregate & coarse EAF slag aggregate was done conforming to IS 383 and the combined gradation was done conforming to IRC SP 68 (2005) at different replacement levels of natural aggregate with EAF slag aggregate to get the maximum density of concrete using trial and error method. The natural coarse aggregate was replaced by 0% ,25% ,50% ,75% & 100 % EAF slag aggregate. The ratio of coarse aggregate (CA) to fine aggregate (FA) was 53:47 for 100 % natural aggregate mix and for the other mixes it was 55:45, this ratio was taken as per IRC SP 68 (2005) .The gradation curves and the percentage replacement of aggregate to get best fit curve are presented in Figure 3.12 to 3.16 & Table 3.4 .respectively .In Figure 3.12 to 3.16 it can be seen that all the curves are best fitted curves and are almost overlapping the mid-limit stated in IRC SP 68 (2005).

Table 3.4 Gradation for mix design

Replacement level of natural coarse aggregate	Sand (Zone III) (%)	Sand (Zone I) (%)	Natural 10mm aggregate (%)	Natural 20 mm aggregate (%)	EAF slag aggregate, 10mm (%)	EAF slag aggregate, 20mm (%)
0%	15	32	19	34	0	0
25%	15	30	13	28.25	4.75	9
50%	15	30	9.35	18.15	5.5	22
75%	15	30	4.81	8.93	13.26	28
100%	15	30	0	0	42	13

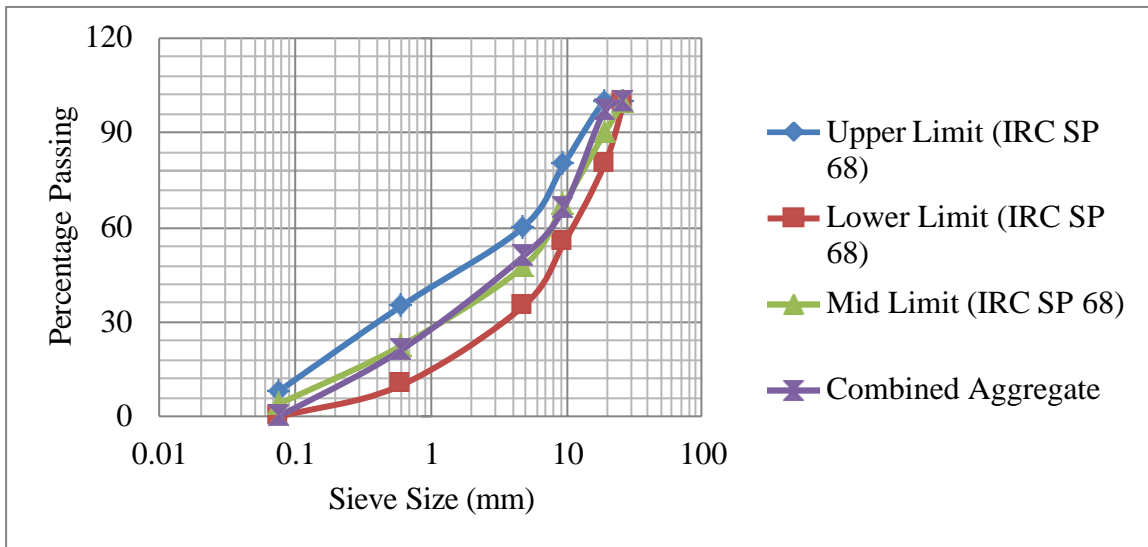


Figure 3.12 Combined Gradation with 100 % Natural Aggregate

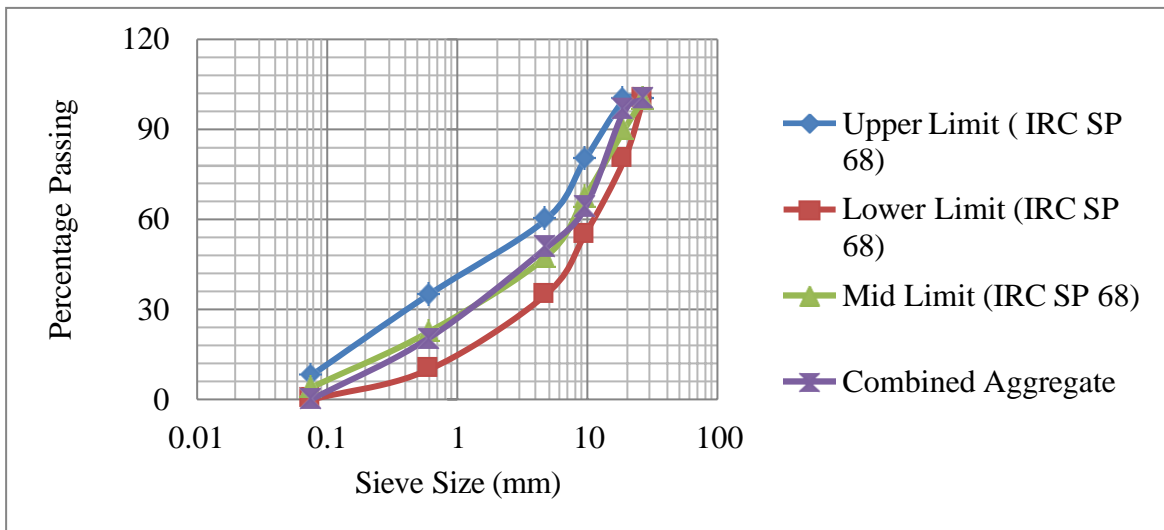


Figure 3.13 Combined Gradation with 75 % Natural Coarse Aggregate and 25 % EAF slag Aggregate

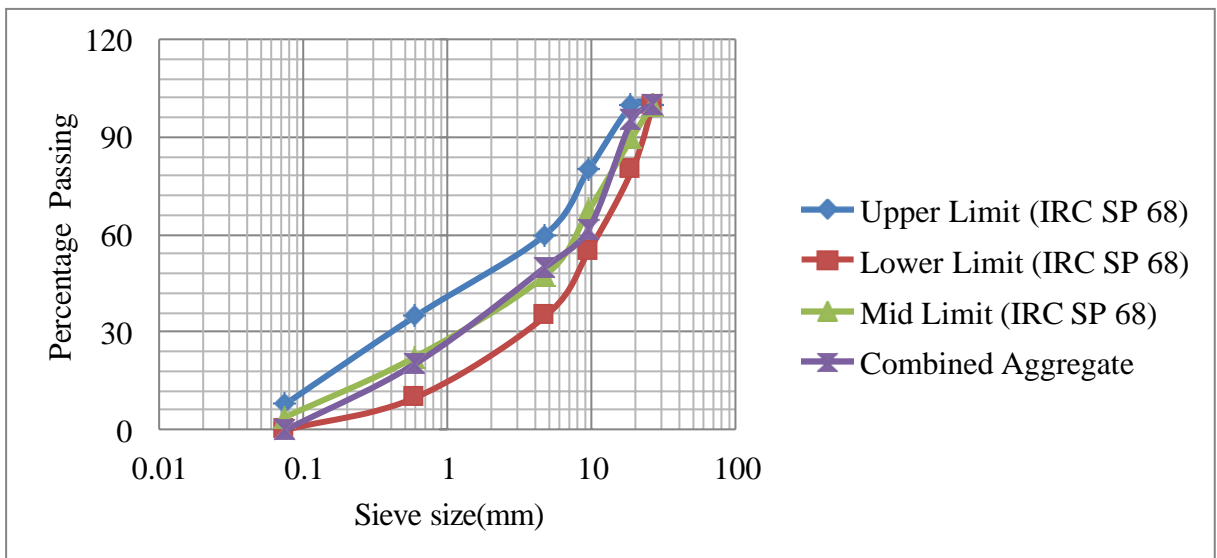


Figure 3.14 Combined Gradation with 50 % Natural coarse aggregate & 50 % EAF slag coarse aggregate

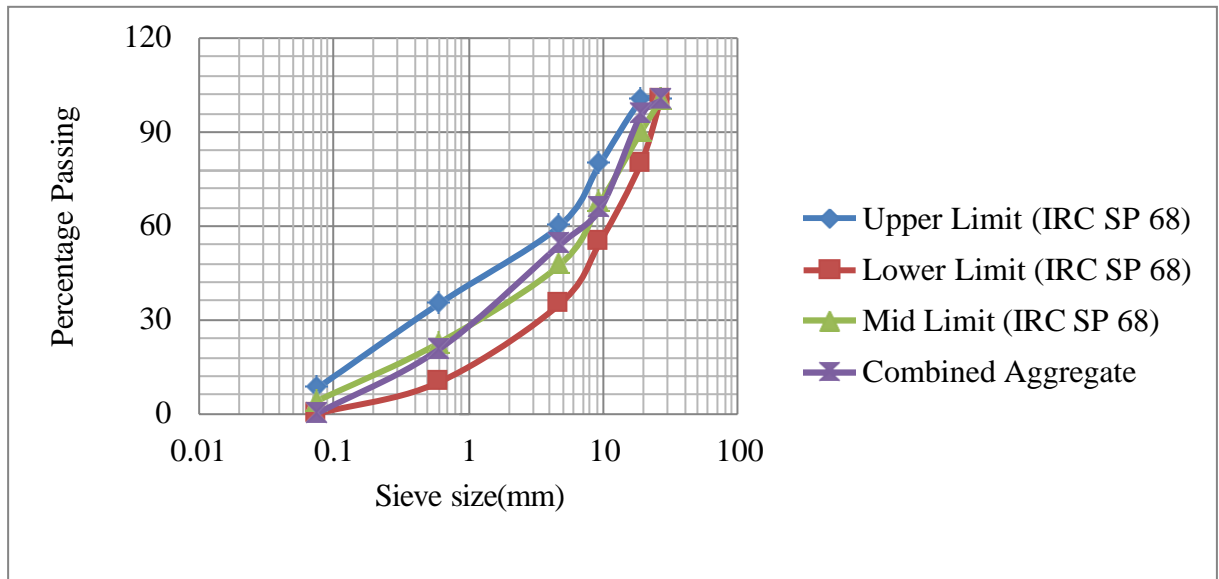


Figure 3.15 Combined Gradation with 25 % Natural coarse aggregate & 75 % EAF slag coarse aggregate

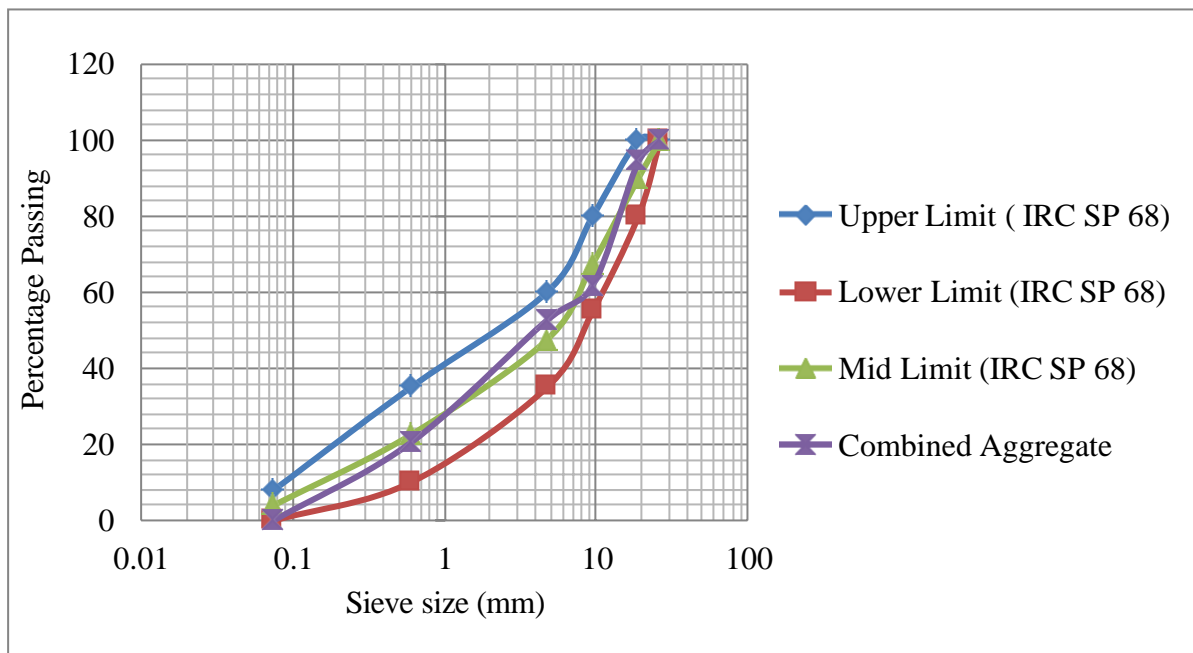


Figure 3.16 Combined Gradation with 100 % EAF slag coarse aggregate

3.4 MIX DESIGN

The properties of different materials that that will be used in study is discussed in section 3.2. The design mainly depends on achieving the maximum density of concrete and hence for each replacement of natural coarse aggregate the gradation has been done separately and has been discussed in section 3.3. As RCCP mix design is different from conventional concrete pavement as it is a zero slump concrete so Abrahm's w/c wil not hold good IRC SP 68 (2015). The RCC mix design are of two types one is used for lean mixtures having aggregate size greater than 37.5mm and proportioning is based on limits of consistency using modified

vebe test and the other method of mix design is for thin sections such as slabs & pavements and proportioning is based on soil compaction method as per ACI 211.3R report (Arnold et al., 2009). Hence in the study the second method has been followed i.e. proportioning based on soil compaction method. Modified proctor test is done to get optimum moisture content (O.M.C) for each mix using the gradation done in section 3.2 at different moisture content. As in conventional concrete pavement there is a target strength for which mix is designed but in RCCP there is no target strength the strength completely depends on the cement content % and the maximum dry density. As the aim of our study is to see the suitability of coarse EAF slag aggregate in RCCP using GGBFS, So for that we will be proportioning twenty mixes with different proportion of EAF slag aggregate and GGBFS to evaluate the effect on mechanical strength properties and durability properties of RCCP with same cement content percentage i.e. 18.5% as per IRC SP 68 at different O.M.C respectively.

Twenty concrete mixes are presented in Table 3.5 below:

Table 3.5 Mix Design

Mix Designation	Natural Fine Aggregate (%)	Natural Coarse Aggregate (%)	Coarse EAF slag Aggregate (%)	Cement (%)	GGBFS (%)
E00	100	100	0	100	0
E25	100	75	25	100	0
E50	100	50	50	100	0
E75	100	25	75	100	0
E100	100	0	100	100	0
E00G30	100	100	0	70	30
E25G30	100	75	25	70	30
E50G30	100	50	50	70	30
E75G30	100	25	75	70	30
E100G30	100	0	100	70	30
E00G50	100	100	0	50	50
E25G50	100	75	25	50	50
E50G50	100	50	50	50	50
E75G50	100	25	75	50	50
E100G50	100	0	100	50	50
E00G70	100	100	0	30	70
E25G70	100	75	25	30	70
E50G70	100	50	50	30	70
E75G70	100	25	75	30	70
E100G70	100	0	100	30	70

3.4.1 Modified Proctor Test

Modified Proctor test was done conforming to ASTM D1557. The material was proportioned according to the gradation given in section 3.2 and the total cementitious material content was 18.5% and for the same 18.5 % was replaced by different percentage of GGBFS. The water content by weight of dry material was varied from 5% and was increased by 1% for

every moisture density mould of same mix. The mould used was 152 mm in diameter and 116 mm height. The hammer used for compaction was 4.54 kg in weight and the mould was compacted in 5 layers by giving 56 blows each layer. The dry density is noted at different moisture content and the curve is drawn from which the O.M.C and the maximum dry density for each mix is found out. The moisture density relation curve are shown from Figure 3.17 to 3.36 and the Table 3.6 represents the O.M.C and the maximum dry density for each mix. From the Table 3.6 it can be inferred that with the increase in slag aggregate percentage replacement the MDD has also increased as slag aggregate is having more density. Since GGBFS is having more specific area it requires more water for hydration and since its density is less than cement so there was increase in O.M.C and slight decrease in MDD.

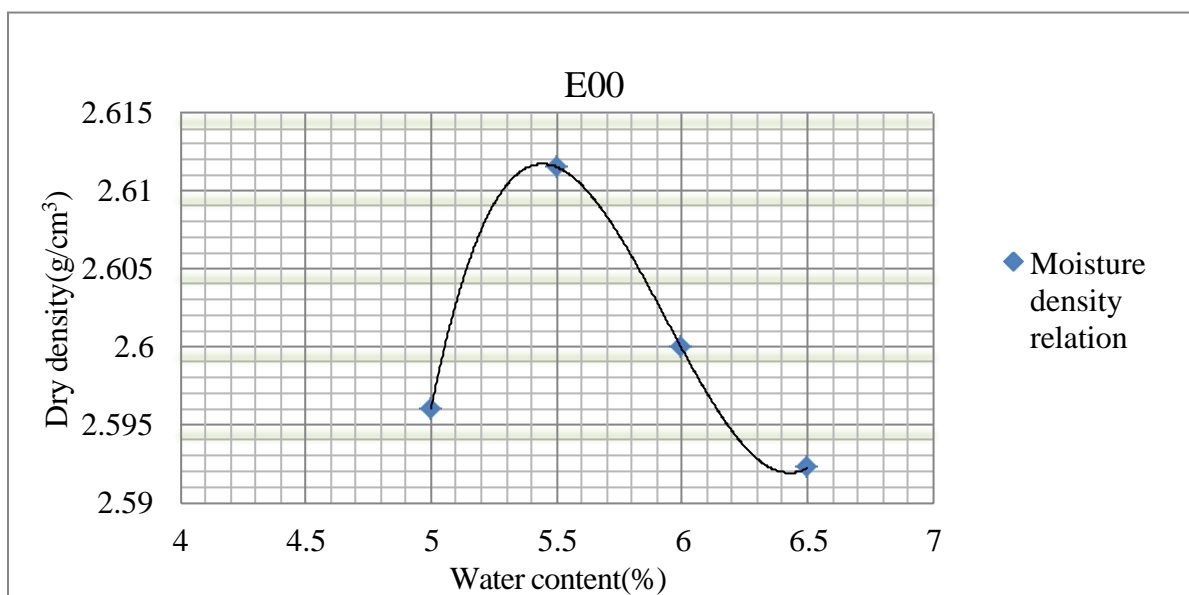


Figure 3.17 Moisture density relation of E00 mix

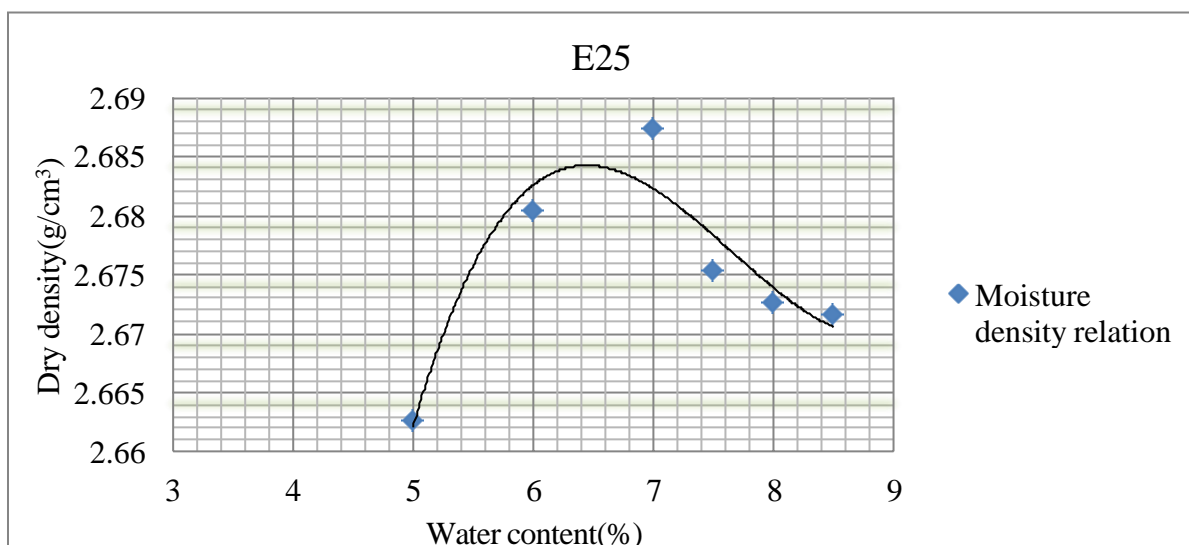


Figure 3.18 Moisture density relation of E25 mix

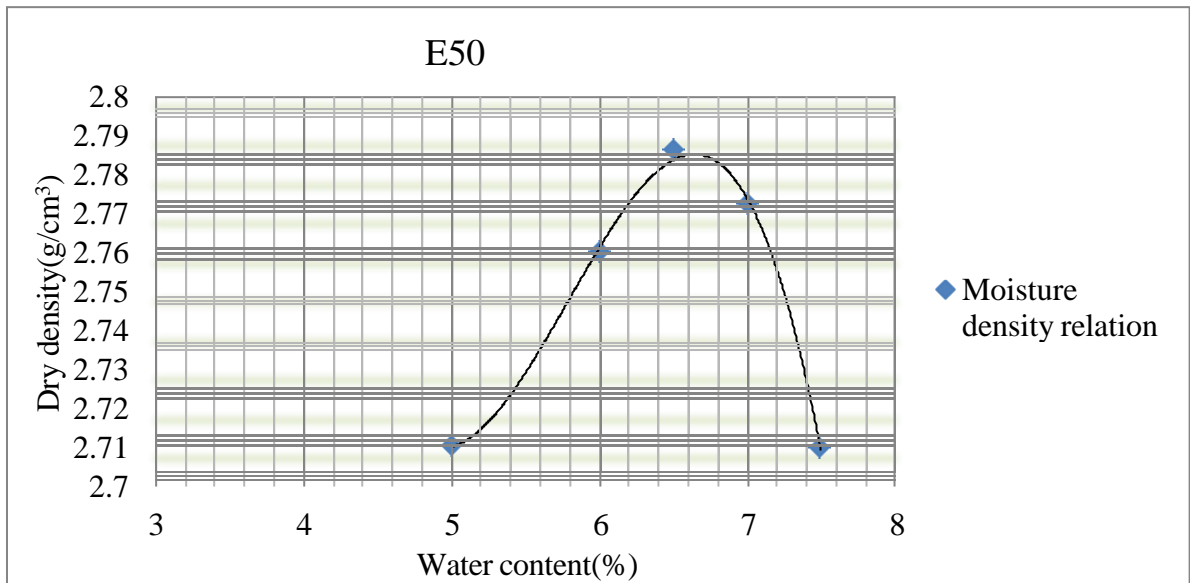


Figure 3.19 Moisture density relation of E50 mix

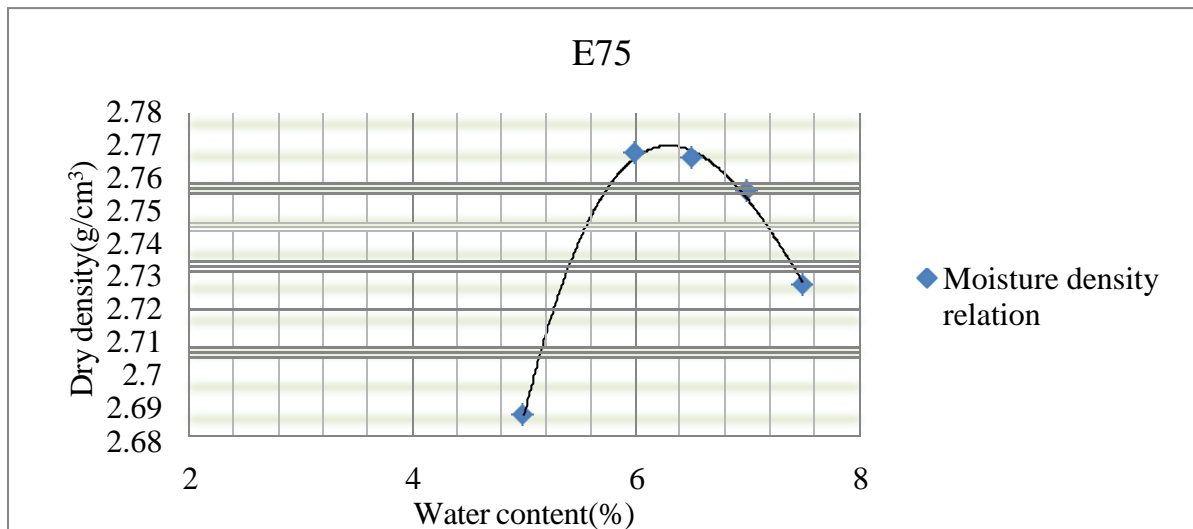


Figure 3.20 Moisture density relation of E75 mix

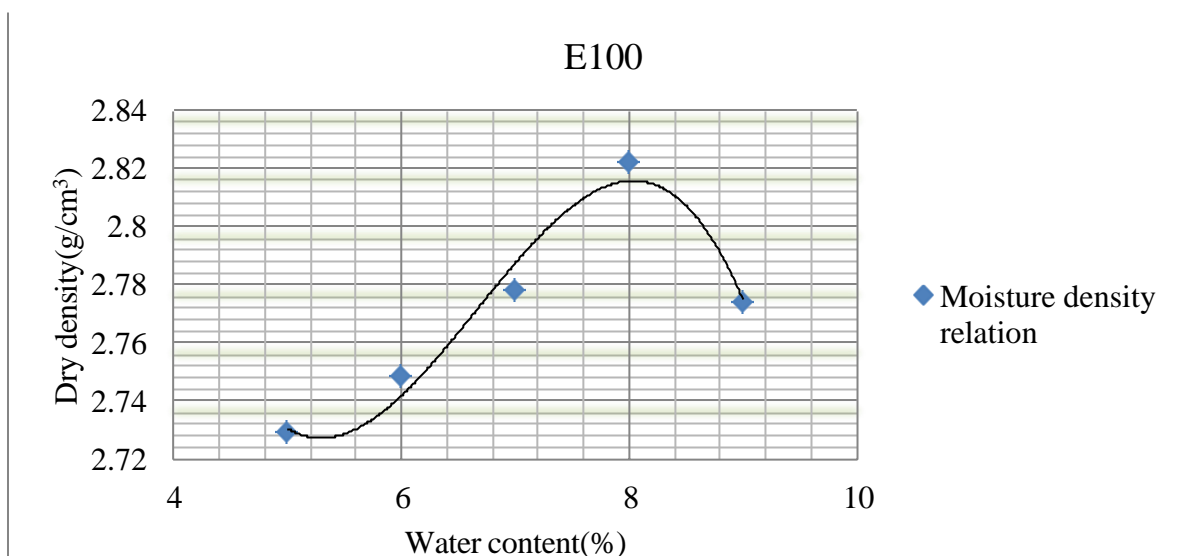


Figure 3.21 Moisture density relation of E100 mix

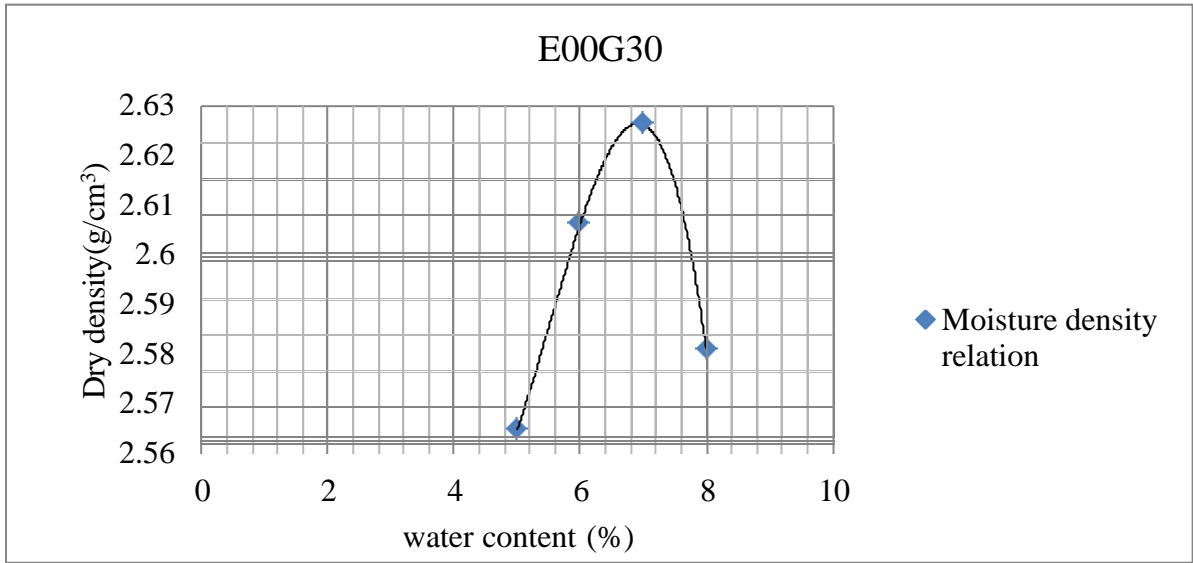


Figure 3.22 Moisture density relation of E00G30 mix

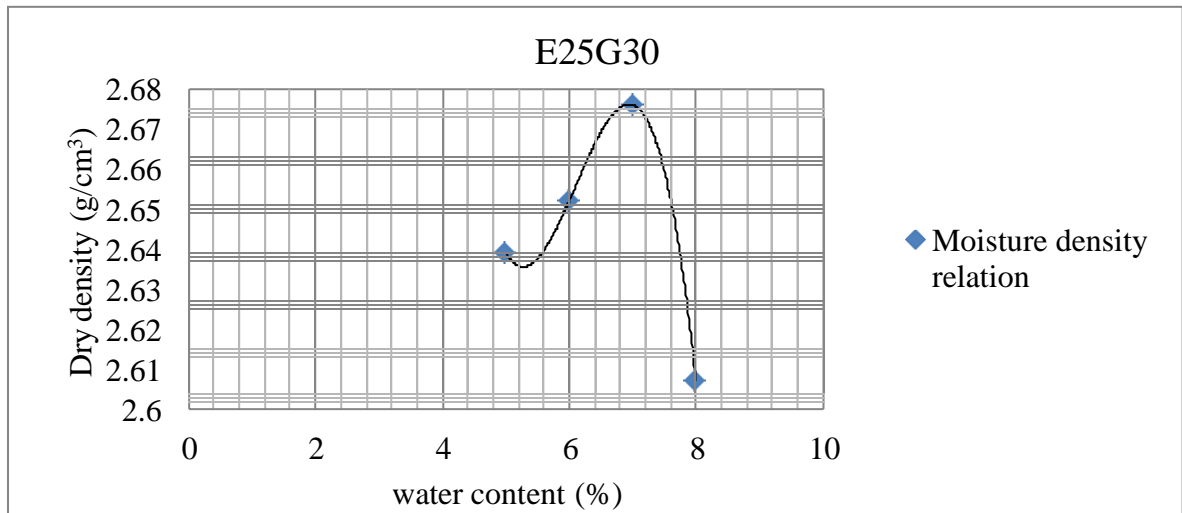


Figure 3.23 Moisture density relation of E25G30 mix

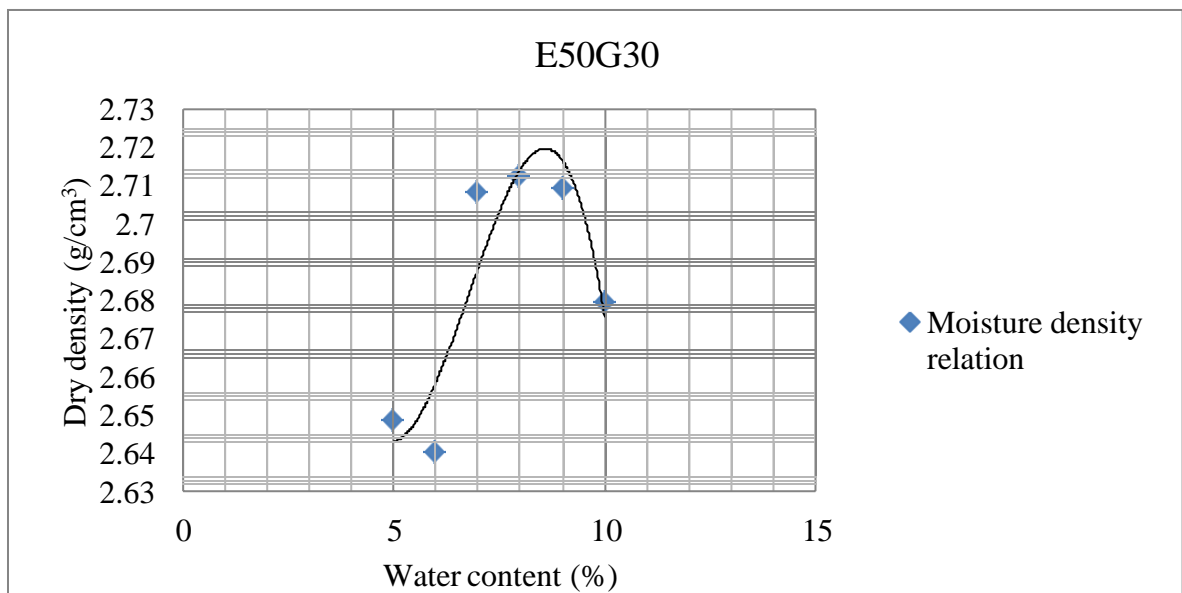


Figure 3.24 Moisture density relation of E50G30 mix

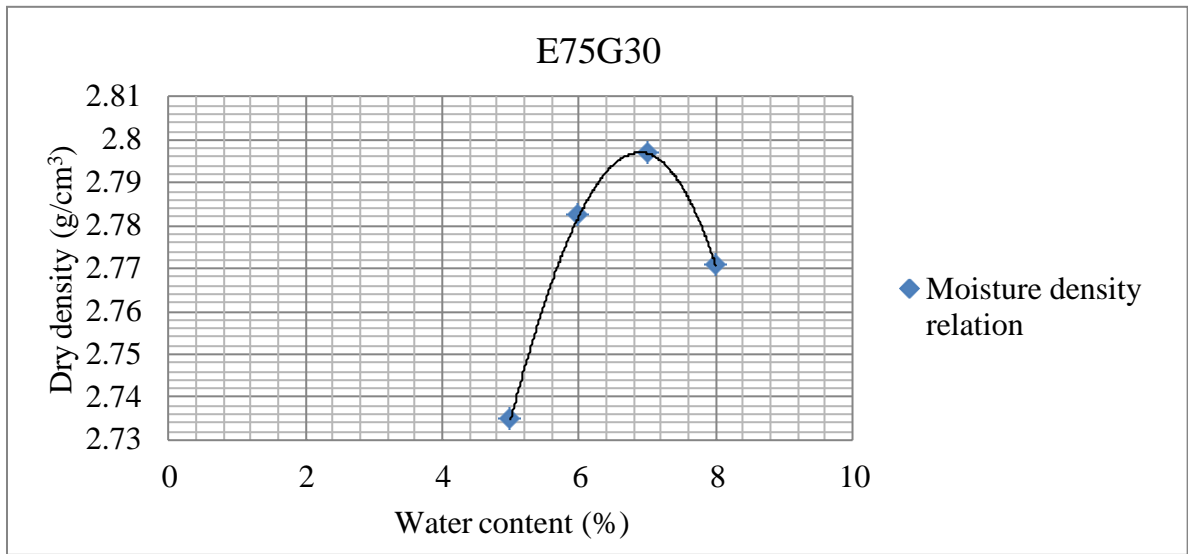


Figure 3.25 Moisture density relation of E75G30 mix

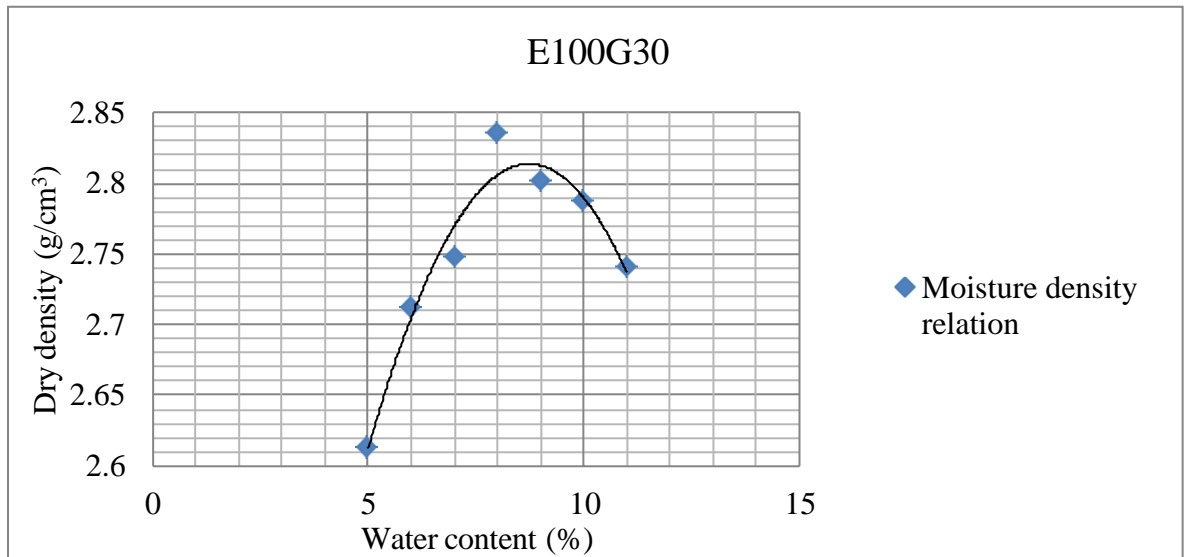


Figure 3.26 Moisture density relation of E100G30 mix

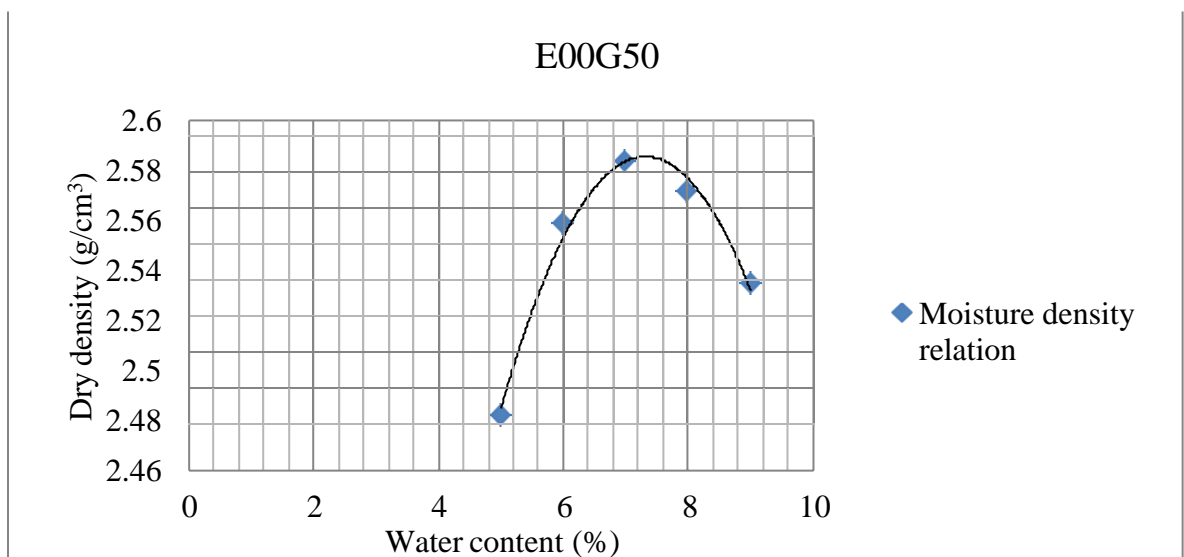


Figure 3.27 Moisture density relation of E00G50 mix

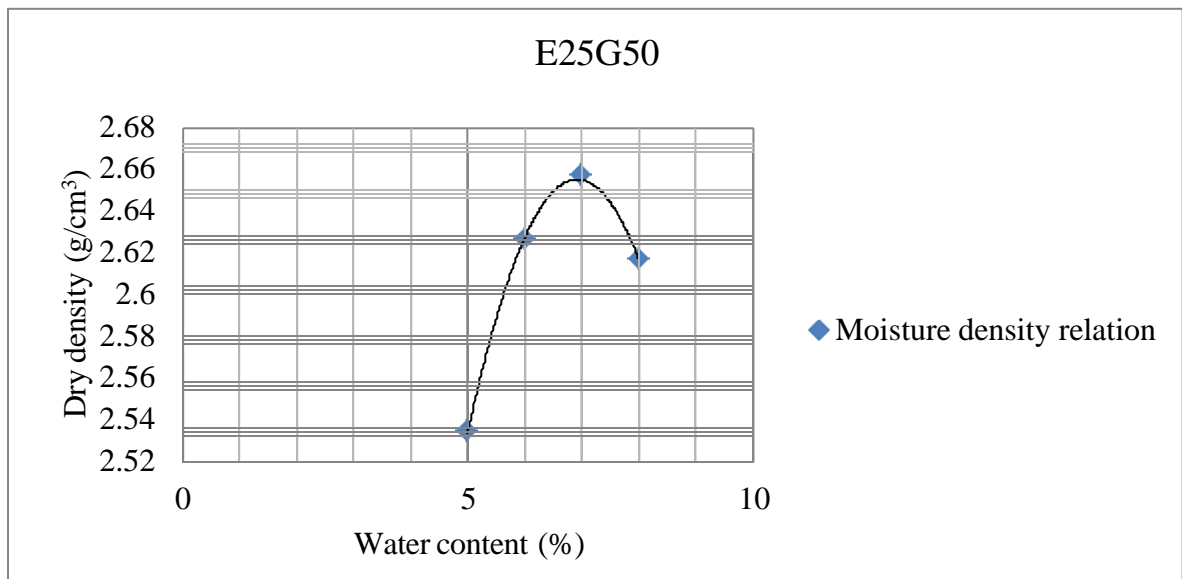


Figure 3.28 Moisture density relation of E25G50 mix

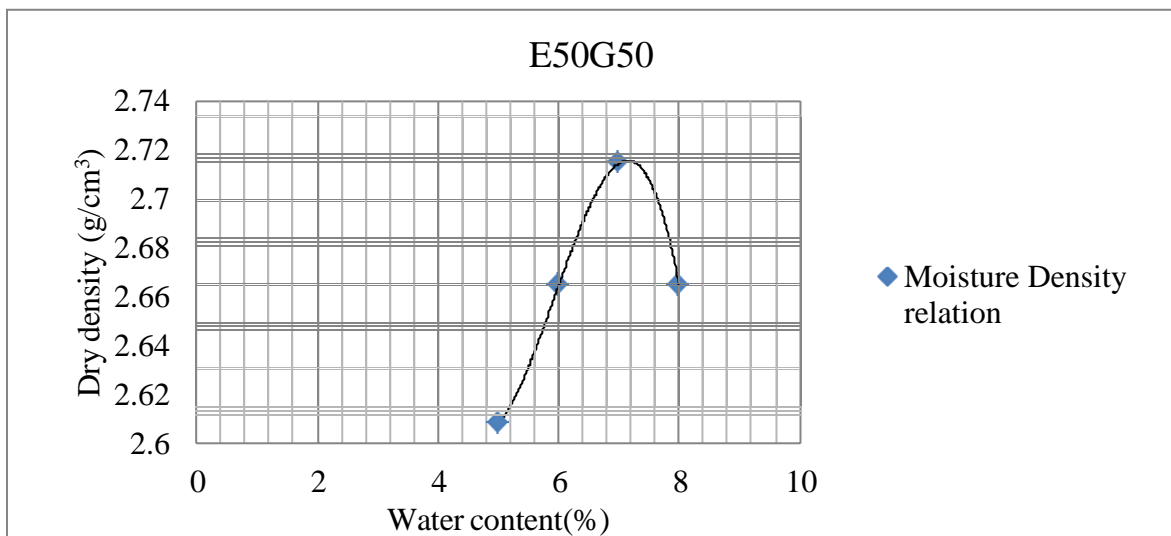


Figure 3.29 Moisture density relation of E50G50 mix

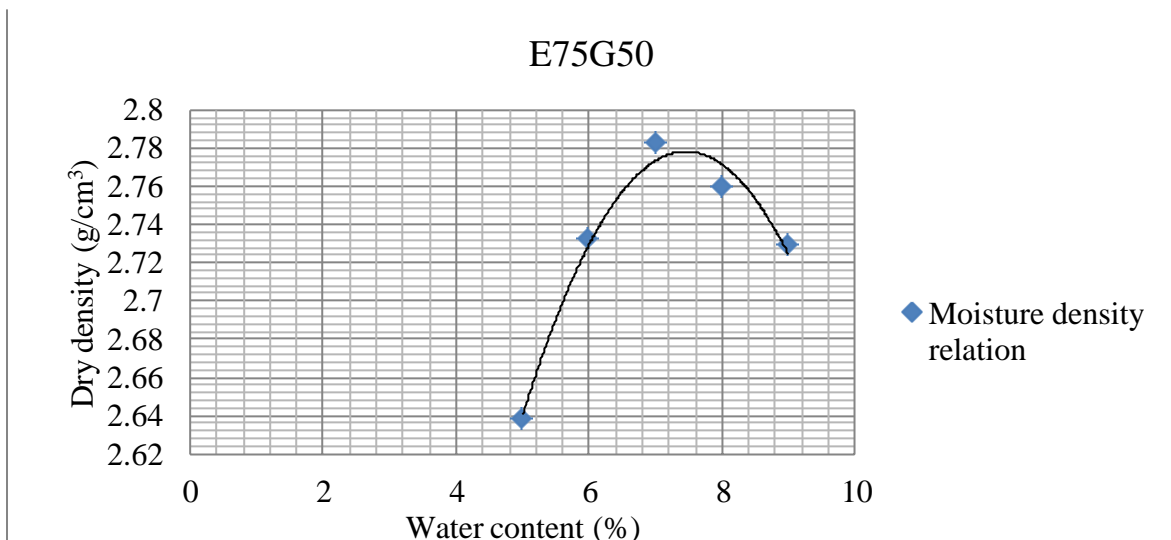


Figure 3.30 Moisture density relation of E75G50 mix

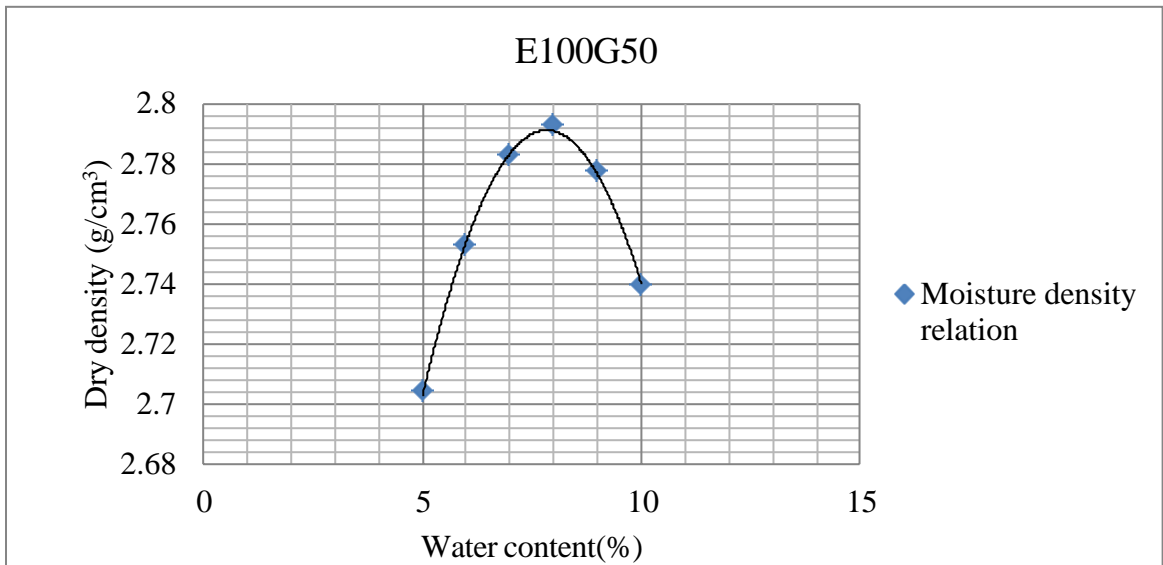


Figure 3.31 Moisture density relation of E100G50 mix

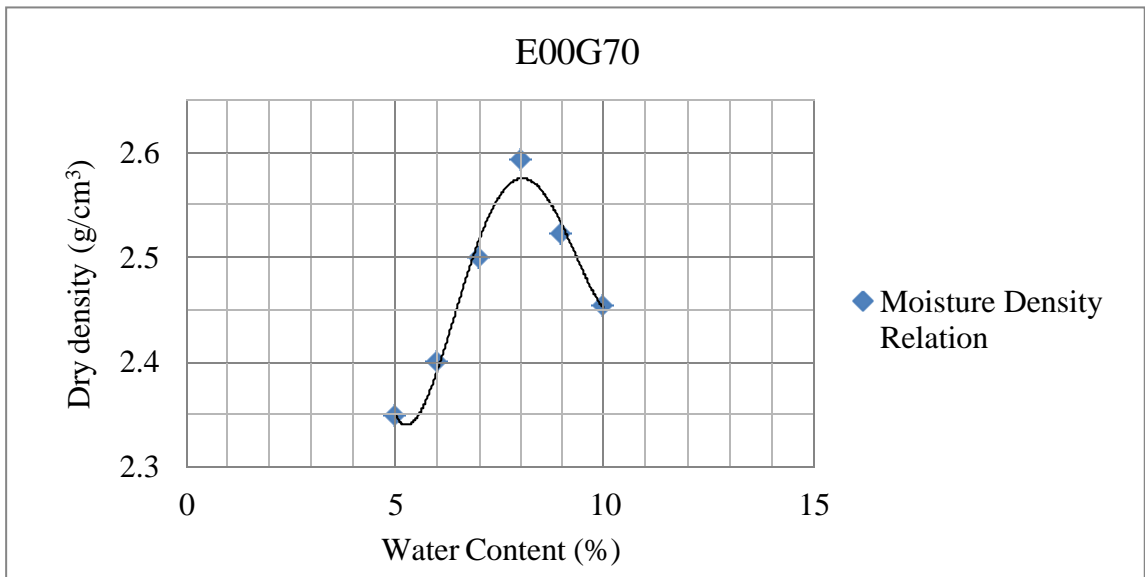


Figure 3.32 Moisture density relation of E00G70 mix

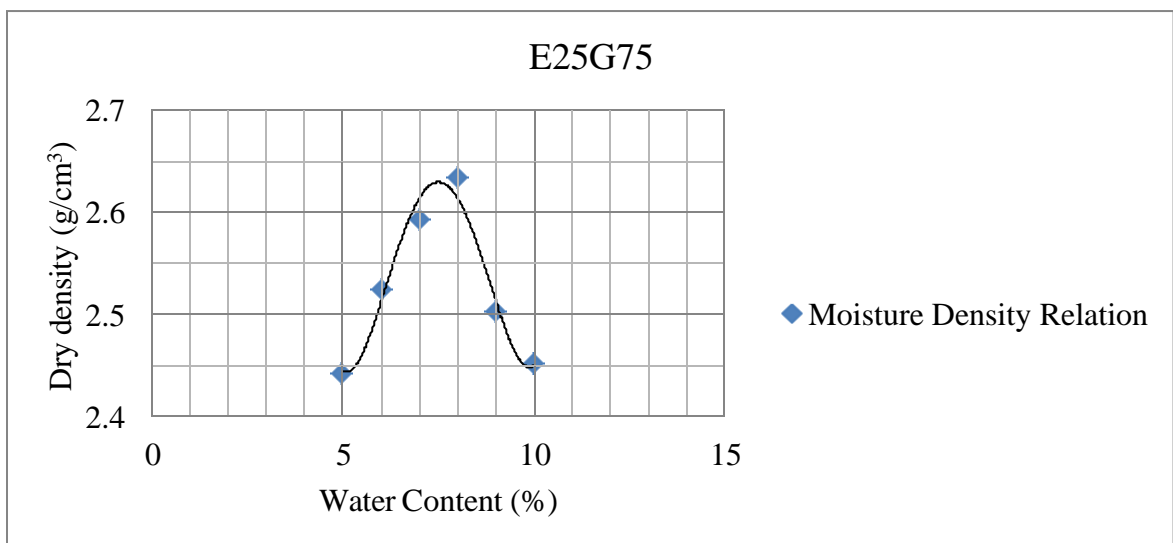


Figure 3.33 Moisture density relation of E25G70 mix

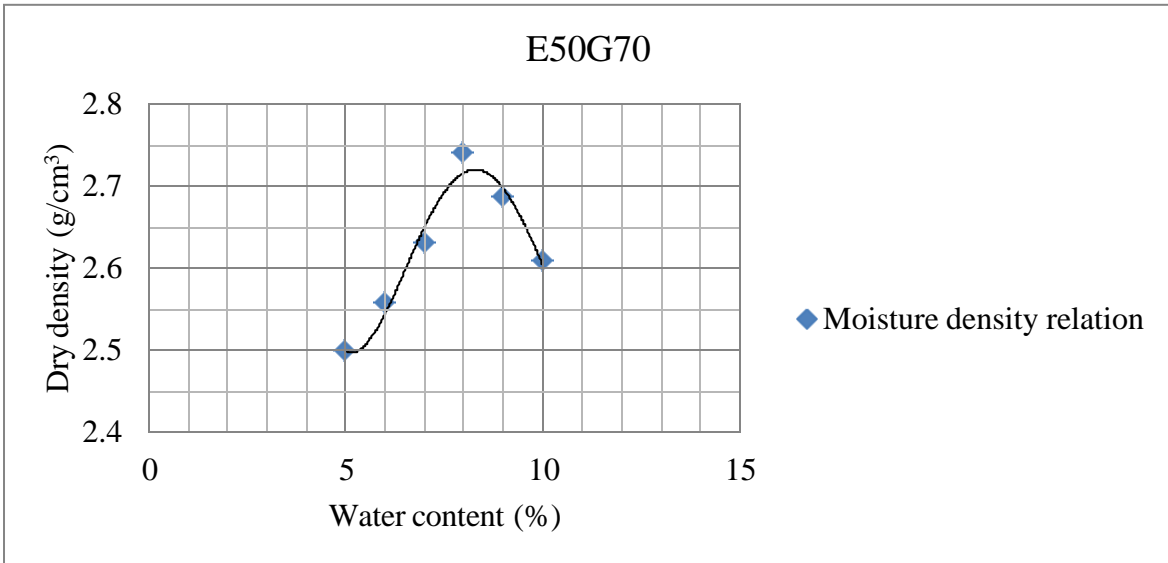


Figure 3.34 Moisture density relation of E50G70 mix

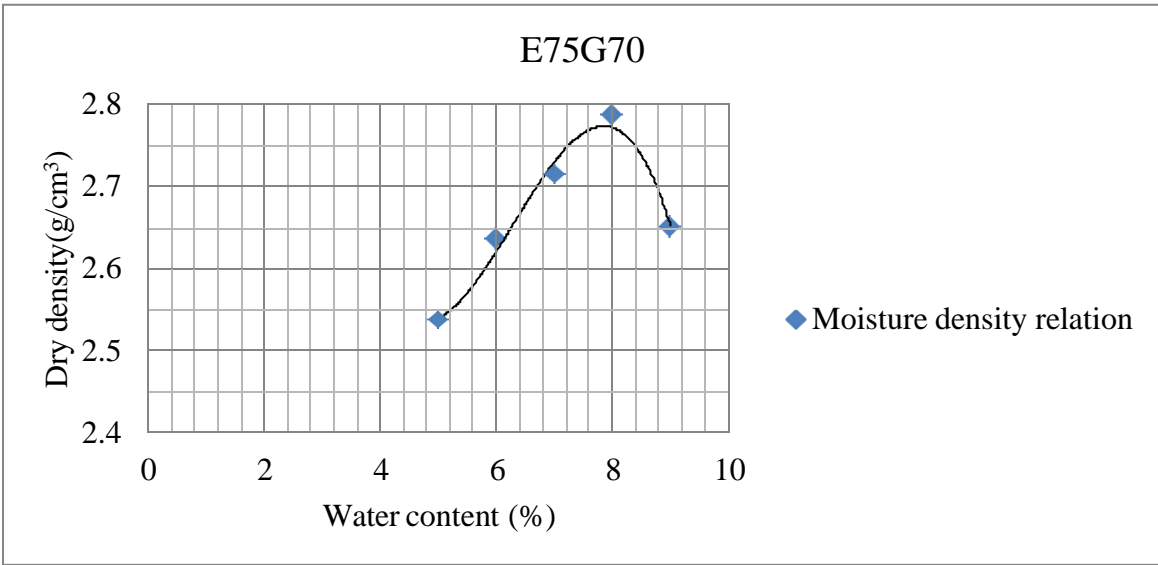


Figure 3.35 Moisture density relation of E75G70 mix

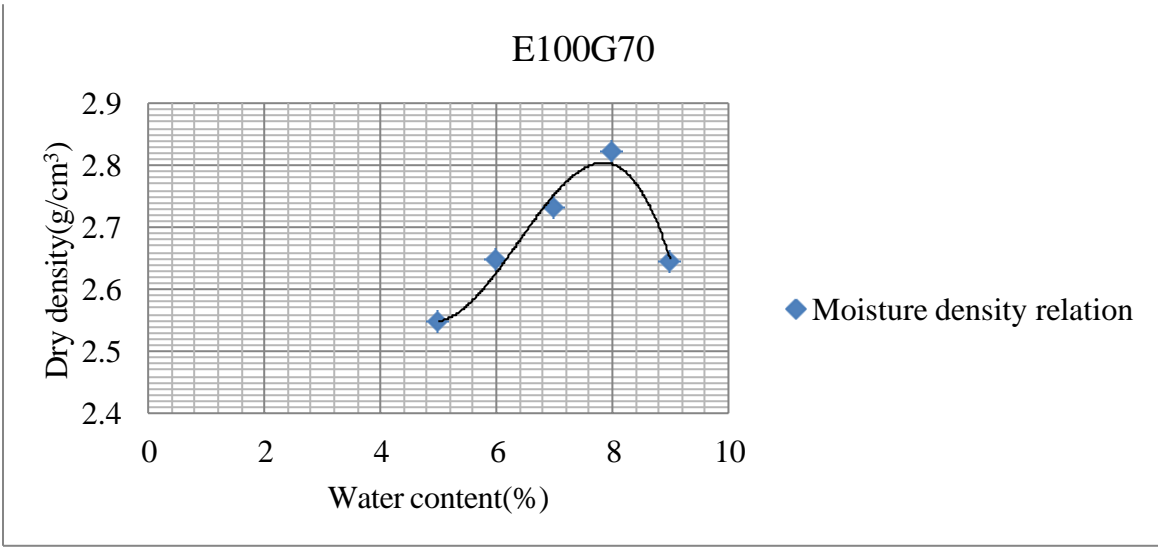


Figure 3.36 Moisture density relation of E00G70 mix

Table 3.6 Modified Proctor results

Mix	O.M.C (%)	M D D (g/cm ³)
E00	5.5	2.615
E25	6.5	2.684
E50	6.7	2.782
E75	6.2	2.768
E100	8.0	2.820
E00G30	6.8	2.626
E25G30	7.0	2.676
E50G30	7.5	2.720
E75G30	6.8	2.796
E100G30	8.0	2.810
E00G50	7.2	2.582
E25G50	7.0	2.658
E50G50	7.2	2.718
E75G50	7.4	2.780
E100G50	8.0	2.792
E00G70	7.4	2.571
E25G70	7.5	2.634
E50G70	7.5	2.728
E75G70	7.8	2.773
E100G70	8.0	2.801



Figure 3.37 Modified Proctor Test

3.4.1 Mix Proportioning

After getting the O.M.C from modified proctor test mix proportioning was done. The proportioning for the mixes had been done as per ACI 211.3R. The cement content was fixed i.e. 18.5 % & the O.M.C. for the all mixes ranged from 5.5 - 8 % which was conforming to ACI 211.3R & IRC SP 68 (2005)(Harrington et al., 2010). The mix proportion of all the castings are given below in Table 3.7:

Table 3.7 Mix Proportioning

Mix	Sand Zone III (Kg/m ³)	Sand Zone I (Kg/m ³)	Cement (Kg/m ³)	GGBF S (Kg/m ³)	Natural Aggregate 20mm (Kg/m ³)	Natural Aggregate 10mm (Kg/m ³)	EAF slag aggregate 20mm (Kg/m ³)	EAF slag aggregate 10mm (Kg/m ³)	Water (Kg/m ³)
E00	293.62	626.29	362.13	0	665.54	371.92	0	0	127.57
E25	291.78	583.56	359.86	0	549.52	252.87	175.07	92.39	149.83
E50	295.19	590.38	364.07	0	357.18	184.00	432.94	108.23	156.24
E75	303.69	607.38	374.55	0	180.79	097.38	566.89	268.46	148.74
E100	295.62	591.24	364.60	0	0	0	827.74	256.20	186.83
E00G30	283.97	605.81	245.16	105.07	643.67	359.70	0	0	152.55
E25G30	288.39	576.78	248.19	106.37	541.43	249.15	172.49	91.03	158.98
E50G30	288.76	577.53	249.30	106.84	349.40	179.99	423.52	105.88	171.09
E75G30	298.32	596.64	257.55	110.37	177.60	95.66	556.87	263.71	160.25
E100G30	294.67	589.34	254.40	109.02	0	0	825.08	255.38	186.23
E00G50	280.82	599.04	173.17	173.17	636.53	355.17	0	0	159.73
E25G50	286.89	573.78	176.91	176.91	540.31	248.63	172.13	90.48	158.65
E50G50	290.18	580.36	178.94	178.94	351.12	180.88	425.60	106.40	165.05
E75G50	293.45	586.90	180.96	180.96	174.70	94.10	547.77	259.41	171.55
E100G50	294.04	588.09	181.32	181.32	0	0	823.32	254.83	185.83
E00G70	278.99	595.18	103.22	240.86	632.38	353.39	0	0	163.09
E25G70	283.09	566.05	104.72	244.34	533.03	245.29	169.81	89.62	167.69
E50G70	287.55	575.11	106.39	248.25	347.94	179.24	421.75	105.43	170.37
E75G70	290.09	580.18	107.33	250.44	172.70	93.02	541.50	256.43	178.75
E100G70	293.41	586.83	108.56	253.31	0	0	821.57	254.29	185.44

3.5 CASTING OF SPECIMEN

The specimens were casted for all the 20 mixes mentioned in Table to evaluate mechanical strength properties, non-destructive test & durability properties for which various specimens were casted.

3.5.1 Preparation of moulds

The plates were fabricated for compacting the concrete in various mould. For cube of 150 * 150 * 150 mm of 100 * 100 mm were fabricated respectively. For beam of 500 * 100 * 100 mm the plate of 170 * 95 mm were fabricated. For cylinder of 150 mm diameter and 100 mm diameter the plate of 295 mm & 95 mm were fabricated. For slab of 500 * 500 * 100 mm the

plate of 175 * 100 mm was fabricated. All the plate and the hilti hammer that was used for compaction is shown in Figure 3.38 .The moulds were conforming to IS 10086 (1982). In Table 3.8 the number of specimen casted for each casting is shown. The Figure 3.38 represents the hammer and the plates used for casting. All the moulds were cleaned before casting and a thin coat of oil was applied on inner surface and top surface so that the concrete should not adhere.



Figure 3.38 (a) Plates used in compaction (b) Moulds casted

Table 3.8 Specimens casted for various tests

Property	Test Age	Specimen Size (mm)	No. of specimen per mix per test age
Compressive Strength	7,28	150*150*150	3
Split Tensile Strength	28	150*300	3
Flexure Strength	7,28	500 * 100 * 100	3
Elastic Modulus	28	150*300	3
Water Absorption	28	100*100*100	3
Abrasion Resistance	28	100*100*100	3
Skid Resistance	28	500 * 500 * 100	1
Effect on hot water curing	28	100*100*100	3

3.5.2 Concrete Mixing

Three stage mixing process was adopted. First the mixer was made wet and then for 5 minutes the aggregates were dry mixed with cement and GGBFS to get a homogenous dry mix & to weather the calcite coating formed on aggregates than half of water was added and

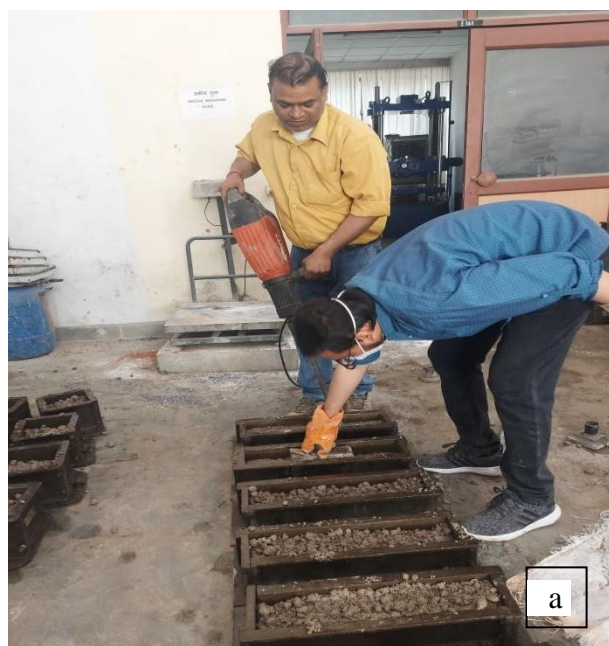
mixed for 8 minutes so that the large pores of EAF slag aggregates are filled as slag aggregate absorbs 90 % water during the first 10 minutes (M. Lam et al., 2018) and remaining water was added and mixed for 5 more minutes. The mix of 320 kg is prepared for each casting as shown in Figure 3.39.



Figure 3.39 (a) & (b) Mixing of concrete

3.5.3 Concreting

The concrete was compacted in 2 layers in beam, 3 layers in cube & cylinder and 2 layers in slab. After filling one layer in each mould the concrete was compacted by giving vibration using vibratory hammer equally covering each corner for 6 seconds and before adding concrete for further layer the previous layer was scratched for a good bonding between concrete layers as shown in Figure 3.40. After compacting each layer in every mould the surface was rubbed using steel float.



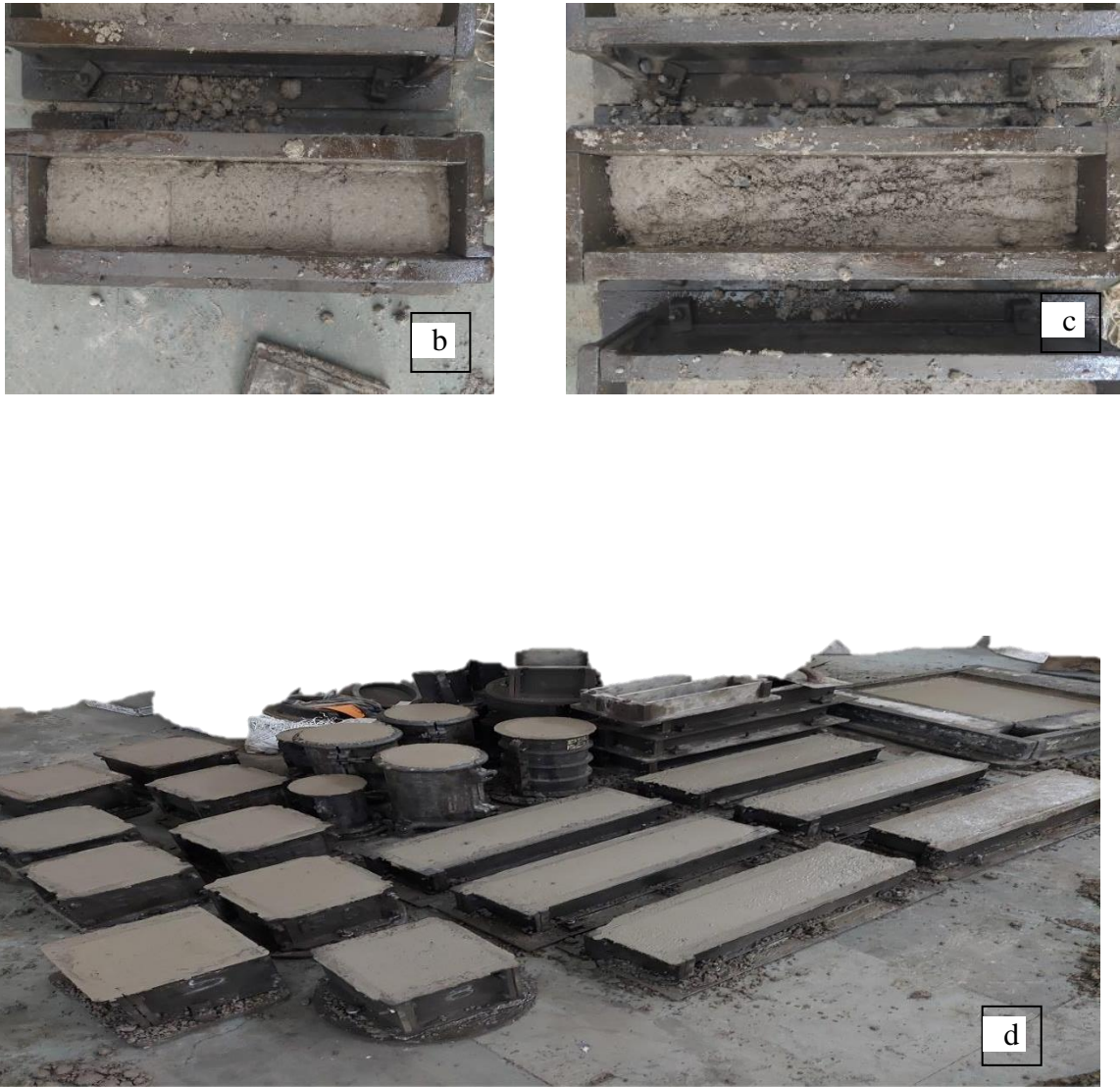


Figure 3.40 (a) compaction of beam ,(b) Beam after compaction of 1 layer,(c) 1st layer of beam scratched,(d) one complete casting

3.5.4 Demoulding & Curing

The specimens were covered with wet jute bags after 1 hour of casting till 24 hours and after that they were demoulded and were kept in curing tank immediately after demoulding. The casting containing 50 % & 70 % GGBFS were demoulded after 36 hours of casting as some breakage were seen during demoulding after 24 hours as in GGBFS there is a delay in setting.



Figure 3.41 Casting after 24 hours of E50G50 mix before demoulding

3.6 SUMMARY

Material properties , gradation for mix design , mix design & casting of specimen were discussed in this chapter. The following details can be summarized as:

- 1.) The various properties of cement, GGBFS, natural aggregate & coarse EAF slag aggregate were determined experimentally to be used in study further. The physical and mechanical properties of EAF slag aggregate were good as compared to natural aggregate except water absorption. Hence durability of concrete is affected by higher water absorption of EAF slag aggregate therefore GGBFS is used as a filler material.
- 2.) The gradation was done for each mix to get a dense gradation of aggregate and hence the matrix will be densified. The modified proctor test was done for each mix to get the water content for mix design. Using the respective gradation of each mix and the water content found out from the soil compaction method was used for mix design as per ACI 211.3R.
- 3.) Triple mixing method was adopted to get a good bonding between the cement paste and aggregate.
- 4.) Specimens casted were tested for mechanical and durability properties which is discussed in detail in chapter 4.

CHAPTER 4

EVALUATION OF PROPERTIES OF ROLLER COMPACTED CONCRETE PAVEMENT

4.1 INTRODUCTION

The specimens casted for all the twenty mixes as in section were tested for fresh properties ,workability , strength properties and durability properties at different ages as shown in Figure 4.1. .In this chapter all the results of the mentioned properties are discussed and also each mix has been compared to its control mix having 100 % natural aggregate.

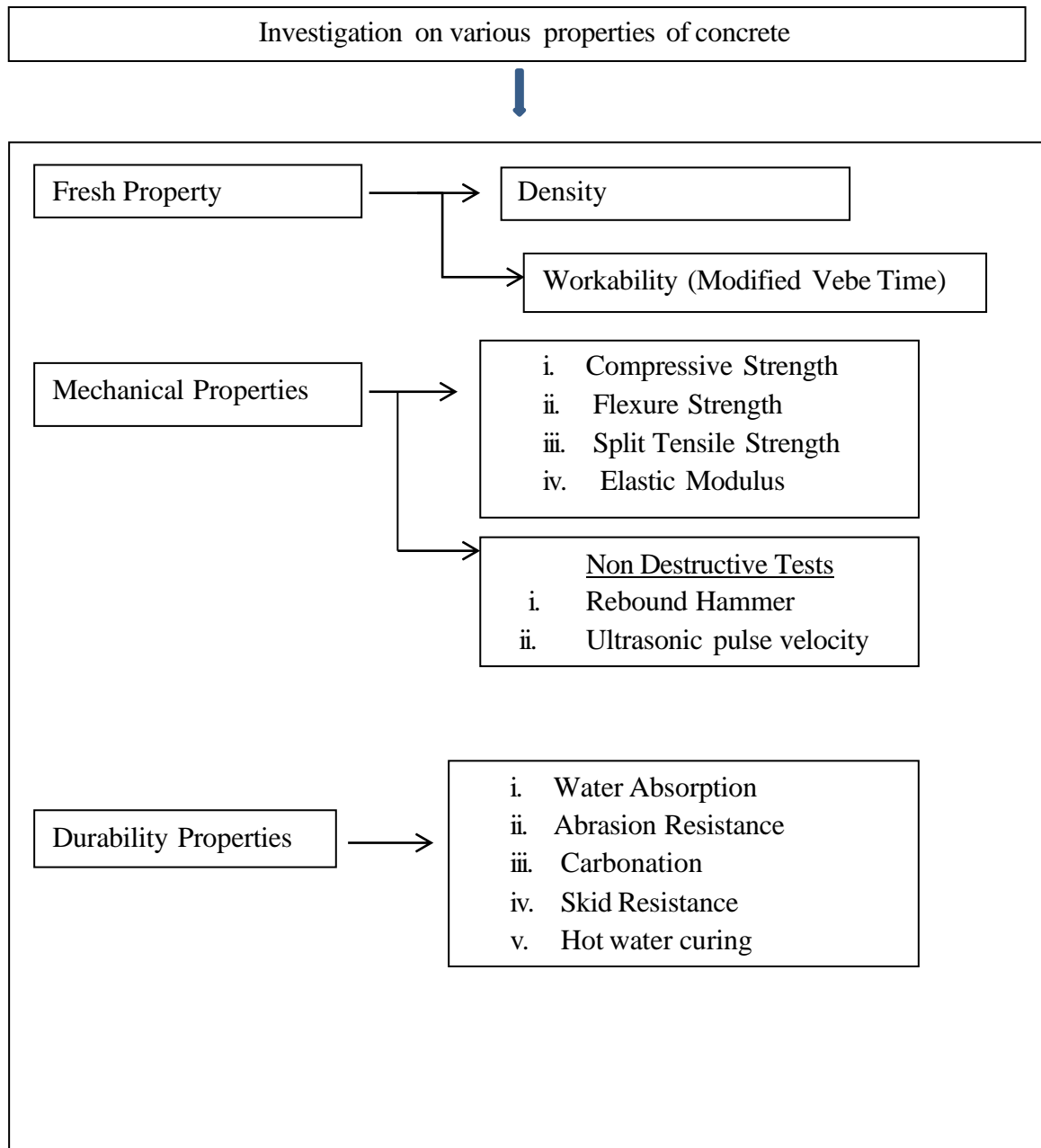


Figure 4.1 Outline of experimental study in chapter 4

4.2 FRESH DENSITY

The fresh density of concrete was calculated for every mix at the time of casting using cubes of 150 * 150 * 150 mm. First the empty weights of the moulds were noted and were marked serial wise. Then the cubes were compacted as mentioned in Section 3.5.3 after that the sides of the cubes were cleaned and weight of the cube was noted. The average of 9 cubes were taken and the results are shown in Figure 4.2 .A general trend of increase in density was seen with the increase in EAF slag aggregate percentage in every set of mix having 0% ,30 % ,50% and 70% GGBFS as the EAF slag aggregates are more denser as compared to natural aggregate. When control mix was compared to mix having 30 % ,50 % ,70 % GGBFS and 100 % natural aggregate it was seen that mix having 30 % GGBFS was having the maximum density and with the increase in GGBFS percentage the density decreased.This same trend was seen when different percentage of GGBFS mix were compared to same percentage of EAF slag aggregate replacement mix i.e. 25 % ,50 % ,75% &100%.It was found that 30 % GGBFS was the optimum amount of GGBFS which can be used to produce a concrete of high density because with the increase in GGBFS percentage more than 30 % there was a decrease in density.

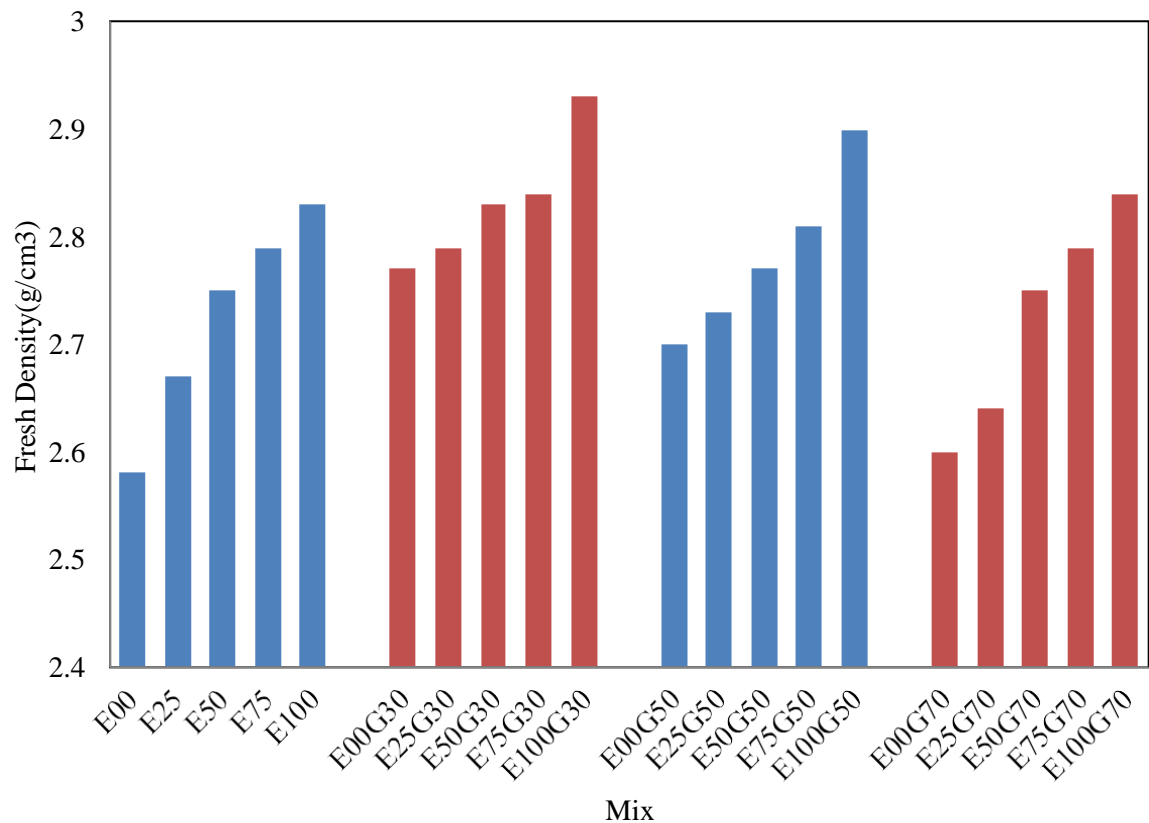


Figure 4.2 Fresh Density

4.3 WORKABILITY

Modified Vebe test was done as RCC is a zero slump concrete and hand rodding compaction will represent poor workability as mentioned in (-207.5R-99 Roller-Compacted Mass Concrete, 1999; Arnold et al., 2009; University of Illinois at Urbana-Champaign et al., 2018). Modified vebe test was done conforming to ASTM C1170. The modified vebe apparatus consists of a Vibrating table, a cylindrical mould of 241 mm diameter and 197 mm height and surcharge of 22.7kg. The fresh concrete was loosely compacted in the cylindrical mould and the surcharge of 23kg was placed on it. The modified vebe time was recorded until and unless a mortar ring is formed between the surcharge edge and the inner surface of the cylinder. This test was done immediately after concrete preparation for each mix as shown in Figure 4.3. The vebe time of each mix is represented in Figure 4.4. The modified vebe time for all the mix's was more than 10 seconds which was conforming to (-207.5R-99 Roller-Compacted Mass Concrete, 1999; University of Illinois at Urbana-Champaign et al., 2018) which may be attributed to low aggregates fine content. The vebe time increases with increase in percentage replacement of EAF slag aggregates as EAF slag aggregates have a rough surface texture. When E00 mix was compared with E100 mix the vebe time increased by 5.6% the percentage increase was less because each mix was having different water content. It was also seen with the increase in GGBFS percentage the workability improved since spherical GGBFS particle acted as ball bearing which reduced the internal friction and prevented the flocculation of cement grains (Husein Bayqra et al., 2022; Siddique and Iqbal Khan, 2011). It was found that with the increase in cement content from 12% – 15 % the RCCP time reduces by 10 % (Rahmani et al., 2020). There was almost 21% decrease in vebe time in mix's containing 70 % GGBFS when compared to respective control mix.

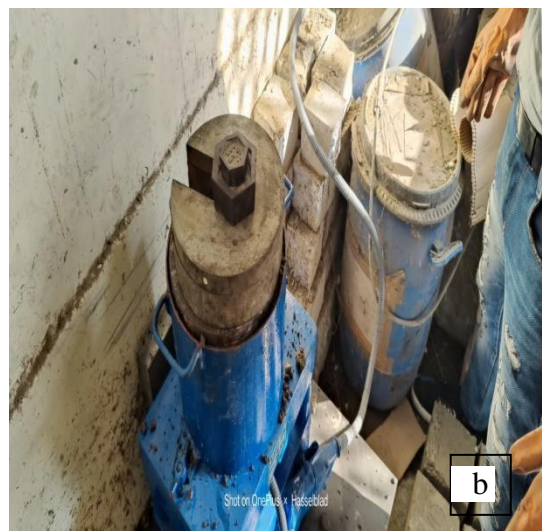




Figure 4.3 (a) Vebe apparatus, (b) Modified vebe test ,(c) Completion of modified vebe test

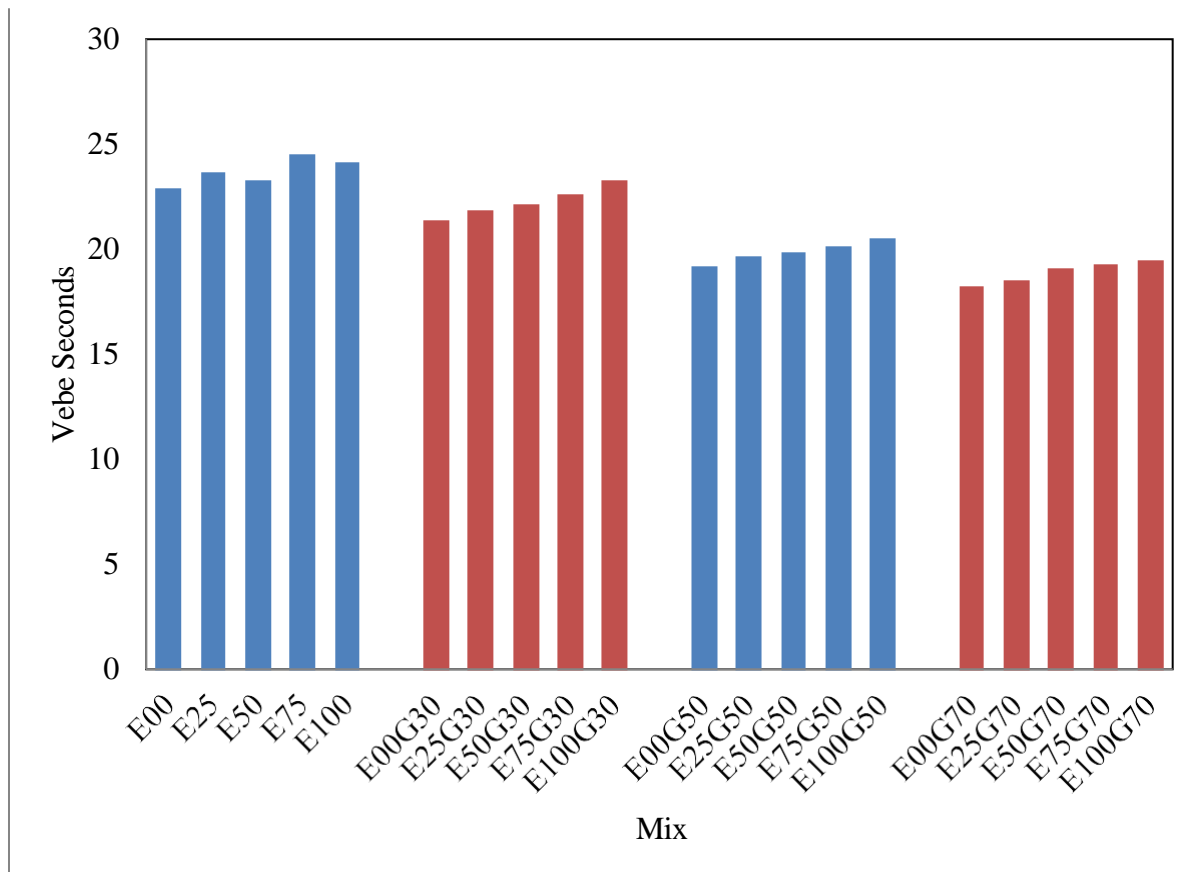


Figure 4.4 Modified vebe test

4.4 MECHANICAL PROPERTIES

4.4.1 Compressive Strength

The compressive test was done conforming to IS 516. The cubes of 150 mm were tested at 7 & 28 days. The area of each cube was calculated before testing and sample size was of 3 cubes as shown in Figure 4.5. The compressive strength was calculated using Equation 4.1.

$$\text{Compressive Strength} = L_d/A_c \quad \text{Equation (4.1)}$$

Where,

L_d =Load (N)

A_c = Area of cross section (mm^2)



Figure 4.5 Compressive strength testing of cube

The results of concrete mix with 100 % cement are presented in Figure 4.6. The 28 day compressive strength of 25 %, 50 % & 75 % natural aggregate replacement with EAF slag aggregate there was increase in strength compared to control mix i.e. E00 and the increase was 12.04%, 9.5%, 19.88% respectively whereas with 100 % EAF slag replacement there was decrease in strength of 4.25% and the same trend was seen in 7 day compressive strength. E00,E25,E50,E75 & E100 mix were having strength more than 40 MPa, So 100 % coarse EAF slag aggregate can be used. E75 mix had achieved the highest compressive strength among all the 5 mix's making 75 % EAF slag aggregate as the optimum replacement of natural aggregate.

The results of concrete mix with 30% GGBFS replacement are presented in Figure 4.7. The 28 day compressive strength of E25G30 ,E50G30 & E100G30 mix had slight increase in strength compared to control mix i.e. E00G30 and whereas in E75G30 an increase of 13.78% . Mixes with 30 % GGBFS replacement achieved strength more than 40 MPa, So as a replacement of coarse natural aggregate 100 % coarse EAF slag aggregate can be used with 30 % GGBFS. The trend seen in fig. is almost same to fig. as E75G30 mix had achieved the highest compressive strength among all the 5 mix's making 75 % EAF slag aggregate as the optimum replacement of natural aggregate with 30 % GGBFS.

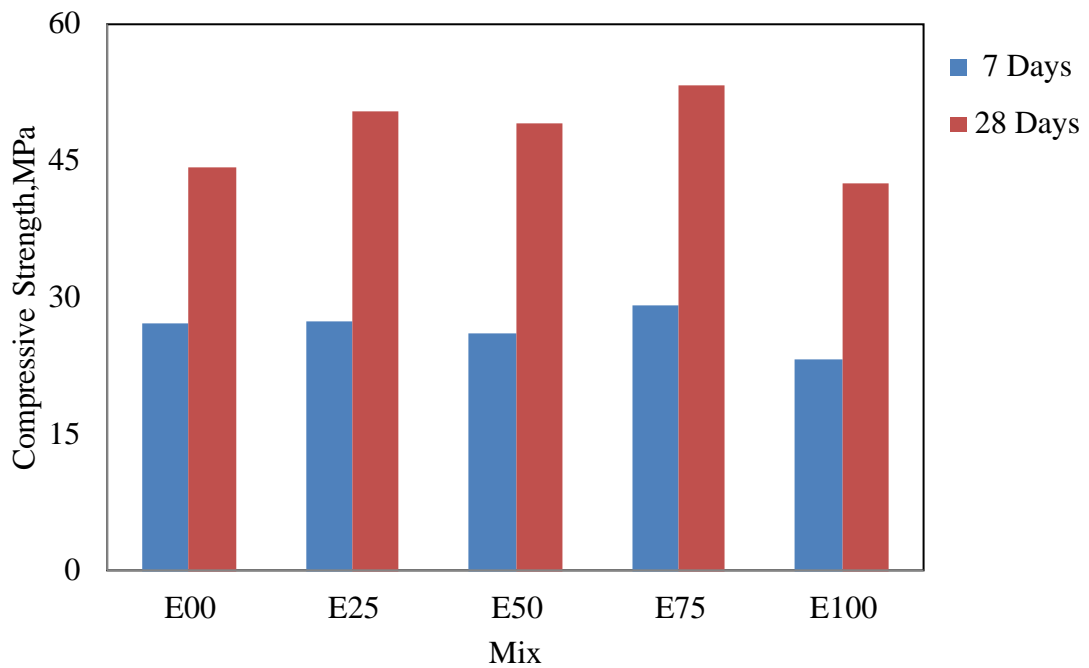


Figure 4.6 Compressive strength of mix containing 100 % cement

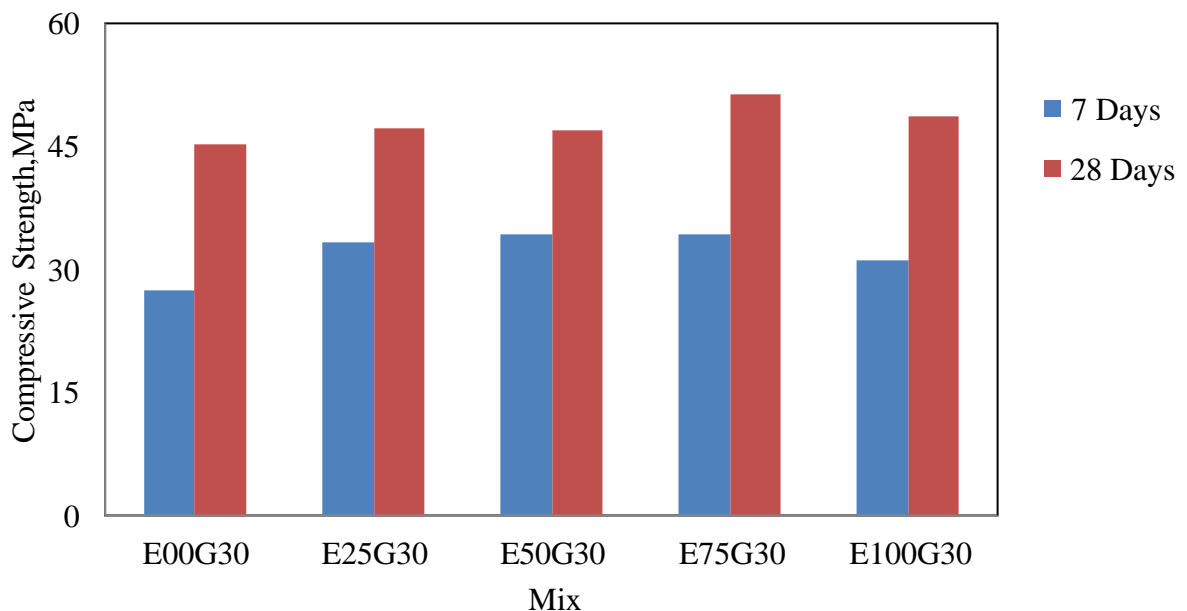


Figure 4.7 Compressive strength of mix containing 30 % GGBFS

The results of concrete mix with 50% GGBFS replacement are presented in Figure 4.8 . The 28 day compressive strength of E25G50 ,E50G50 ,E75G50 & E100G50 mix had slight decrease in strength compared to control mix i.e. E00G50 and whereas in 7 day compressive strength vice versa was seen. Mixes with 50 % GGBFS replacement achieved strength more than 40 MPa, So 100 % coarse EAF slag aggregate can be used with 50 % GGBFS.



Figure 4.8 Compressive strength of mix containing 50 % GGBFS

The results of concrete mix with 70% GGBFS replacement are presented in Figure 4.9 . The 28 day compressive strength of E25G70 mix had slight increase in strength compared to control mix i.e. E00G70 and whereas in E50G70 ,E75G70 & E100G70 increase of 10.94%,12.80%, 20.02% respectively was seen. Mix's with 70 % GGBFS replacement achieved strength less than 40 MPa, So even 100 % coarse natural aggregate cannot be used with 70 % GGBFS.

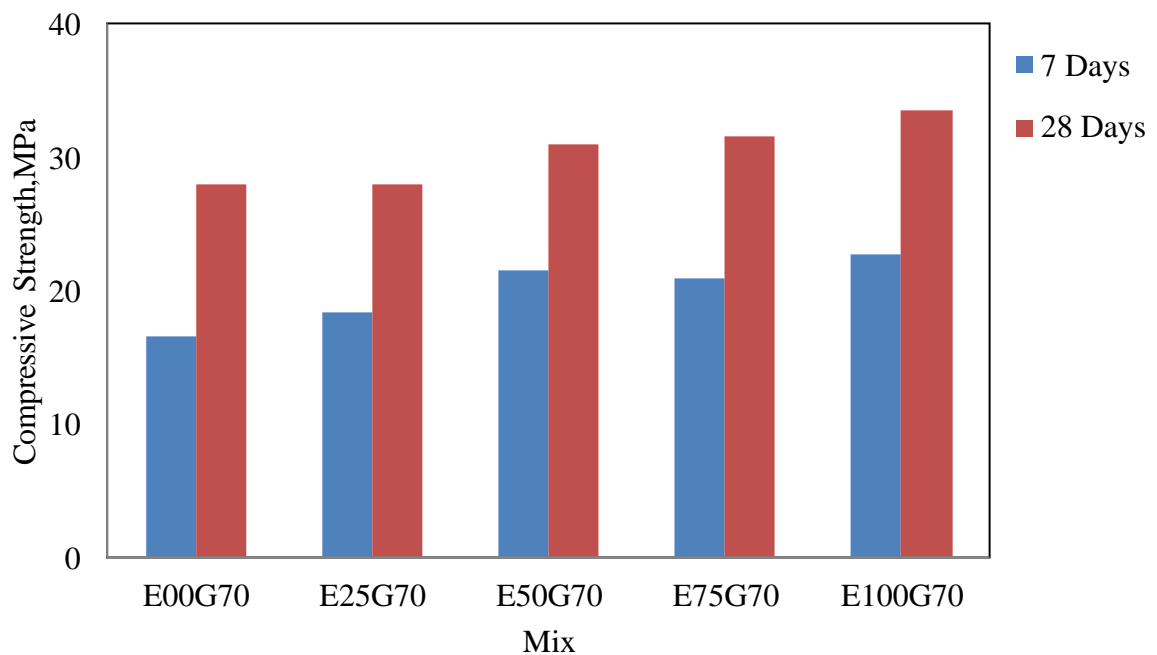


Figure 4.9 Compressive strength of mix containing 70 % GGBFS

In the every set of mix i.e.(same Cement content percentage and same GGBFS percentage) but different replacement of EAF slag aggregate (i.e. 0, 25 ,50 ,75 & 100 %) it was seen that there was increase in compressive strength when compared to respective control mix it was due to the three stage mixing process in which the calcite coating formed on the aggregates during their stabilization process is removed which improves the bonding between the aggregate and cement paste i.e. Interfacial Transition Zone (ITZ) was improved. And on the other hand EAF slag aggregate being more denser produced concrete of high density which further improved the strength.(M. Lam et al., 2018; Lam et al., 2017; M. N.-T. Lam et al., 2018b) have stated in there result that compressive strength of control mix is more than mix containing EAF slag aggregate at different replacement. The mix containing high GGBFS percentage i.e. 50 % & 70 % was blue green in colour this can be attributed to complex reaction of sulfide sulphur with other compounds of cement but with oxidation this colour diminishes at later age(Aghaeipour and Madhkhan, 2017).The mix's containing 30 % GGBFS with different percentage of EAF slag aggregate was having comparable strength when compared to control mix i.e. E00,E25,E50,E75 & E100 respectively this may be attributed to the utilization of free lime present in EAF slag aggregate after stabilization also forming $\text{Ca}(\text{OH})_2$ which will further react with GGBFS to form a secondary C-S-H gel which will further densify the pores of the EAF slag aggregate as stated by (Husein Bayqra et al., 2022; Mardani-Aghabaglou and Ramyar, 2013; Saluja et al., 2019).Mix's containing 50 % GGBFS was having decrease in strength when compared to control mix i.e. E00,E25,E50,E75 & E100 respectively and the decrease was 1.9 % ,14.75%,13.34%,21.93%,3.24% respectively, Stil al mix's containg 50 % were having strength more than 40 MPa.But there was a tremdous decrease in strength in mixes containing 70 % GGBFS when compared to control mix i.e. E00,E25,E50,E75&E100 respectively and the decrease was 37.30 % ,44.48%,36.81%,40.77%,21.07% respectively.The decrease in strength in 50 % & 70 % GGBFS mix's is because GGBFS is not as good as cement in terms of strength contribution at early age(M. N.-T. Lam et al., 2018b) and there may also be lesser availability of $\text{Ca}(\text{OH})_2$ for primary hydration reaction and hence 70 % GGBFS acted more as a filler as compared to binder(Saluja et al., 2019).Fig. shows the failure pattern of the concrete cubes and it can be seen that the mix containing different percentage of slag aggregate and GGBFS all were having same failure pattern as E00 mix and all the mixes were having satisfactory failure conforming to IS 516 (Part 2/Sec 1) 2017.

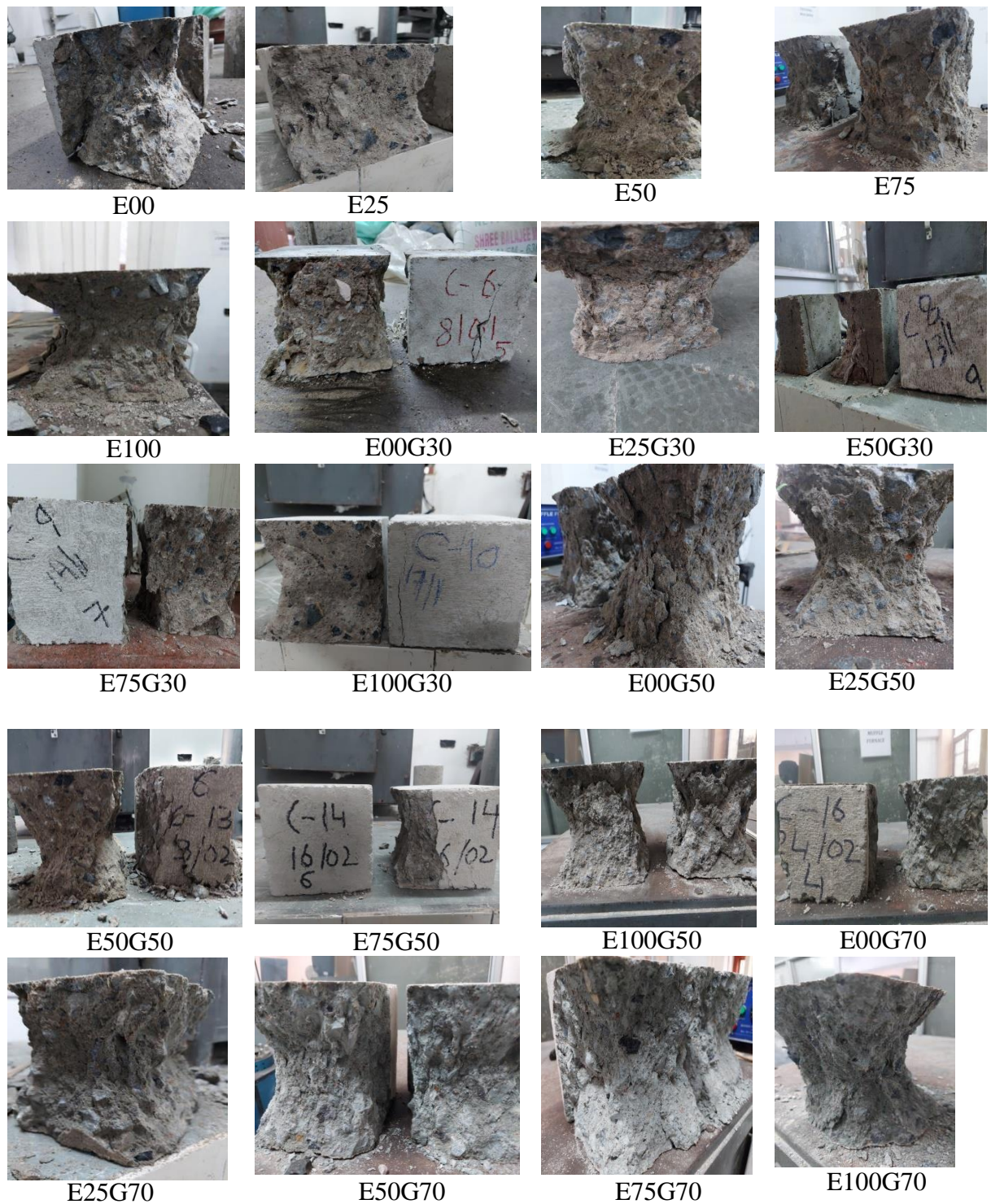


Figure 4.10 Failure pattern of cubes in compressive testing

4.4.2 Flexure Strength

The flexure strength test was done conforming to IS 516 on 500*100*100 mm prism and using equation the flexural strength of beam was calculated for 7 and 28 days.

$$\text{Flexure strength} = P l / b d^2 \quad \text{Equation (4.2)}$$

If $a < 13.33 \text{ cm}$

Where a is the distance between line of fracture and nearest support

If $a > 13.33 \text{ cm}$

$$\text{Flexure strength} = \frac{3P a}{b d^2} \quad \text{Equation (4.3)}$$

Where,

P = Maximum load

l = Span on which beam is supported

b = width of the specimen

d = depth of specimen

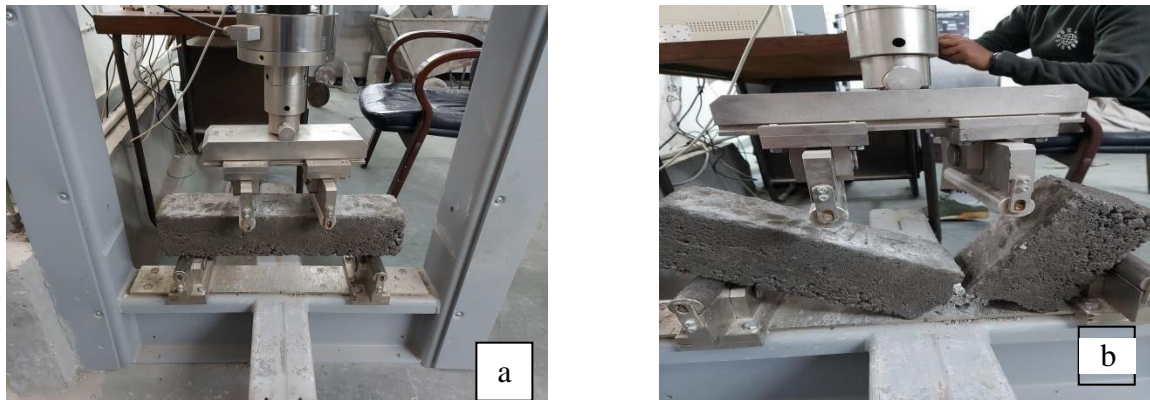


Figure 4.11 Flexure Testing

The results of concrete mix's with 100 % cement are presented in Figure 4.12. The 28 day flexural strength of 25 % ,50 % &75 % EAF slag aggregate mix was more than the control mix i.e. E00 whereas with 100 % EAF slag replacement there was decrease in strength of 8.53%.The change in flexure strength in 7 day prisms were same as of 28 days. The increase in strength may be attributed to the three stage mixing as in compressive strength and the decrease in strength in 100 % EAF slag aggregate mix due to the increase in porosity of the aggregate in concrete , the weak ITZ formed due to improper bonding due to presence of calcite layer even after dry mixing and due to absence of some of the chemical composites formed due to presence of natural aggregate. All the mixes were having strength more than 4.95 MPa, So 100 % coarse EAF slag aggregate can be used.E75 mix had achieved the highest flexural strength among all the 5 mix's making 75 % EAF slag aggregate as the optimum replacement of natural aggregate with 100 % cement.

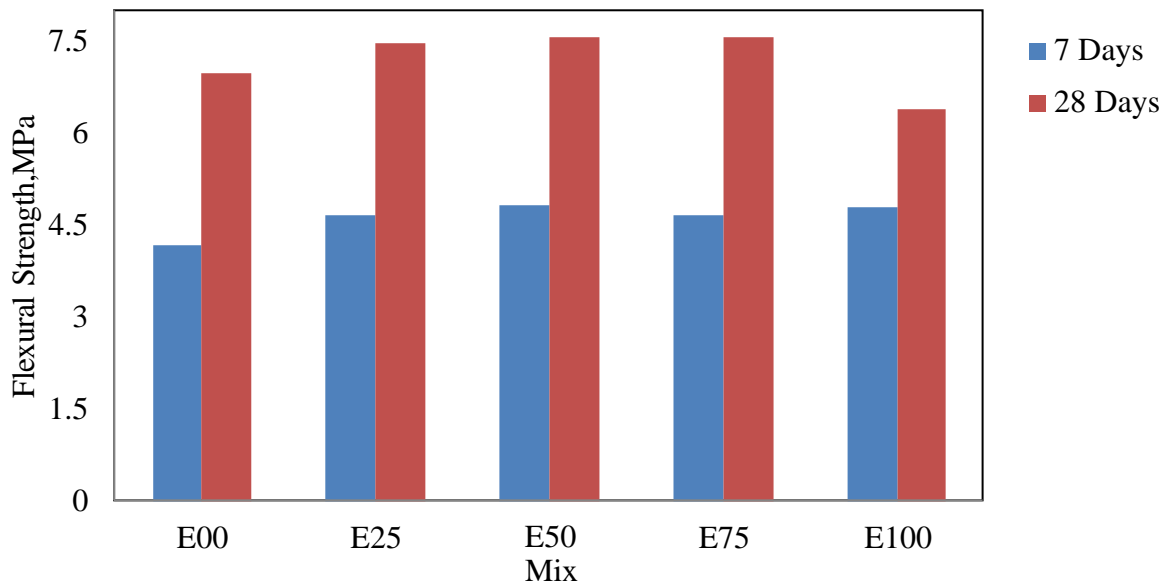


Figure 4.12 Flexure test on 100 % cement mixes

The results of Concrete mix with 30% GGBFS replacement are presented in Figure 4.13. The 28 day flexure strength of E25G30 ,E50G30 ,E75G30 & E100G30 mix had slight increase in strength compared to control mix i.e. E00G30. Mixes with 30 % GGBFS replacement achieved strength more than 4.95 MPa, So 100 % coarse EAF slag aggregate can be used with 30 % GGBFS. The results of concrete mix with 50% GGBFS replacement are presented in Figure 4.14. The 28 day flexure strength of E25G50 & E50G50 mix had slight decrease in strength compared to control mix i.e. E00G50 whereas in mix E75G50 & E100G50 had tremendous decrease in strength i.e. 13.73%. Mixes with 50 % GGBFS replacement achieved strength more than 4.95 MPa, So 100 % coarse EAF slag aggregate can be used with 50 % GGBFS. The results of concrete mix with 70% GGBFS replacement are presented in Figure 4.15. The 7 day & 28 day flexure strength of E25G70,E50G70 ,E75G70 & E100G70 mix had increase in strength compared to control mix i.e. E00G70. Mix with 70 % GGBFS replacement achieved strength more than 4.95 MPa, So 100 % coarse EAF slag aggregate can be used with 70 % GGBFS.

The results for GGBFS mix's for flexure strength was having the same trend as in compressive strength i.e. control mix's and 30 % GGBFS mixes were having comparable strength and with the increase in GGBFS percentage (i.e. 50 % & 70 %) there was decrease in strength and this decrease in strength was due to same reason as stated in compressive strength. But all the 20 mixes were having flexural strength more than 4.95 MPa.

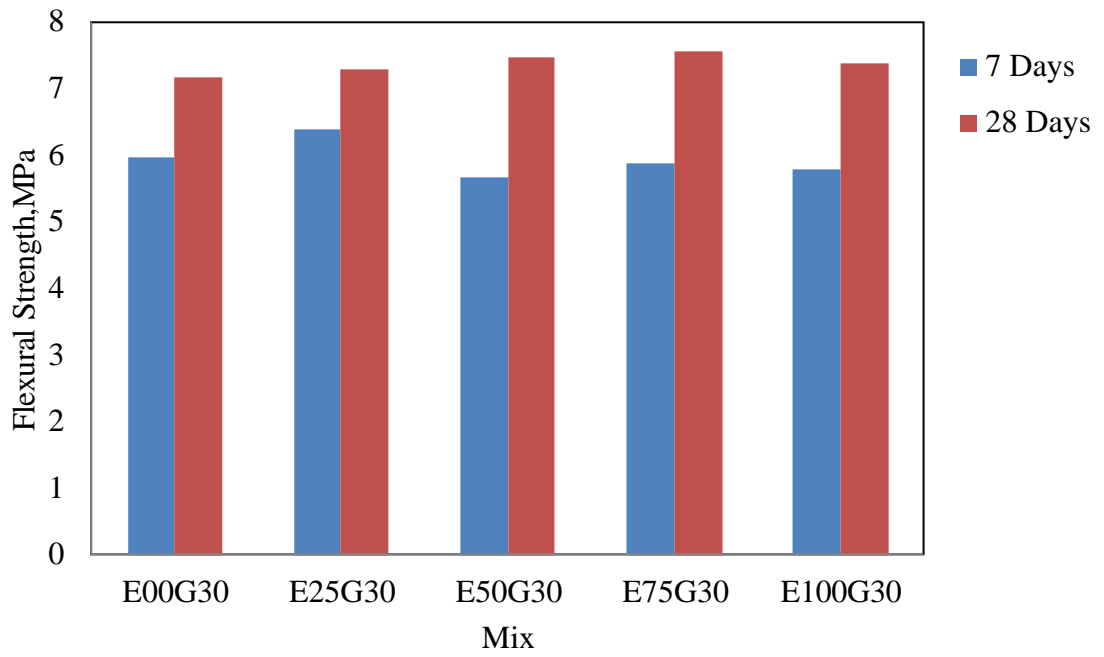


Figure 4.13 Flexure test on 30 % GGBFS mixes

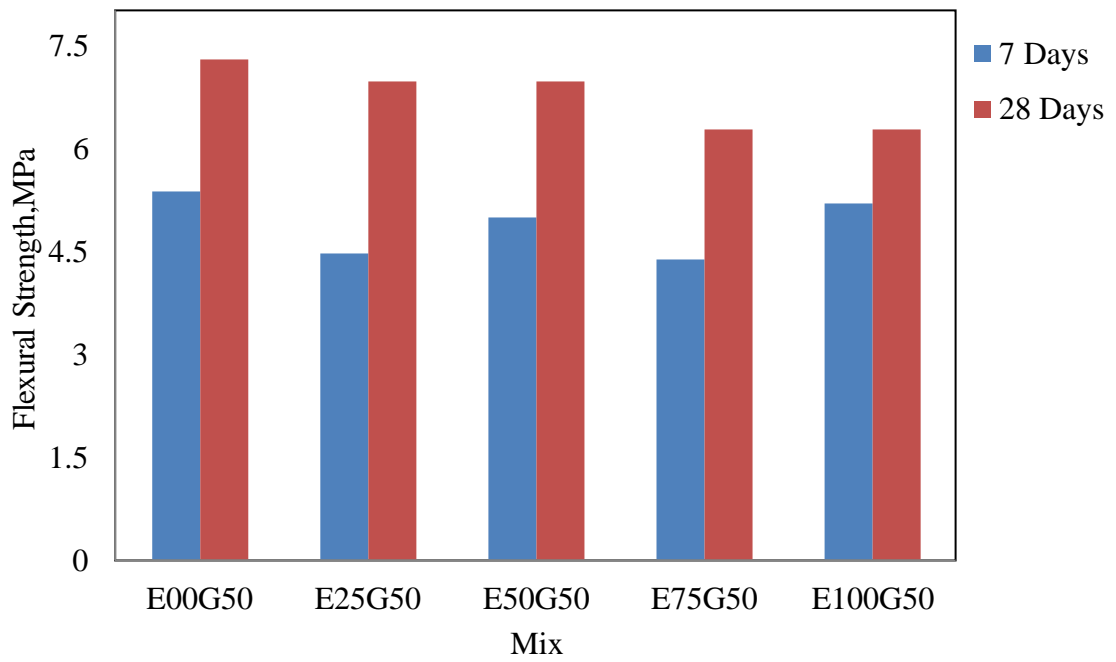


Figure 4.14 Flexure test on 50 % GGBFS mixes

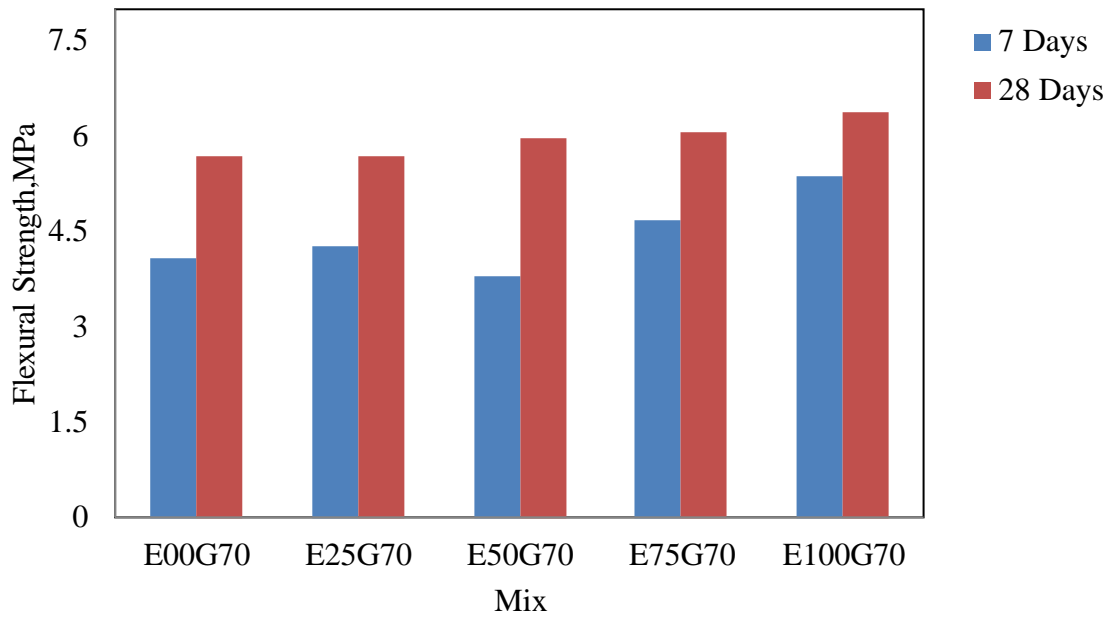


Figure 4.15 Flexure test on 70 % GGBFS mixes

4.4.3 Split Tensile Strength

The split tensile strength test was done conforming to IS 516 on 150 mm diameter and 300 mm height cylinder as shown in Figure 4.16, using equation the split tensile strength was calculated for 28 days.

$$\text{Split Tensile Strength} = \frac{2P}{\pi LD} \quad \text{Equation (4.4)}$$

Where,

P = Maximum load

L = Length of Cylinder

D = Diameter of specimen

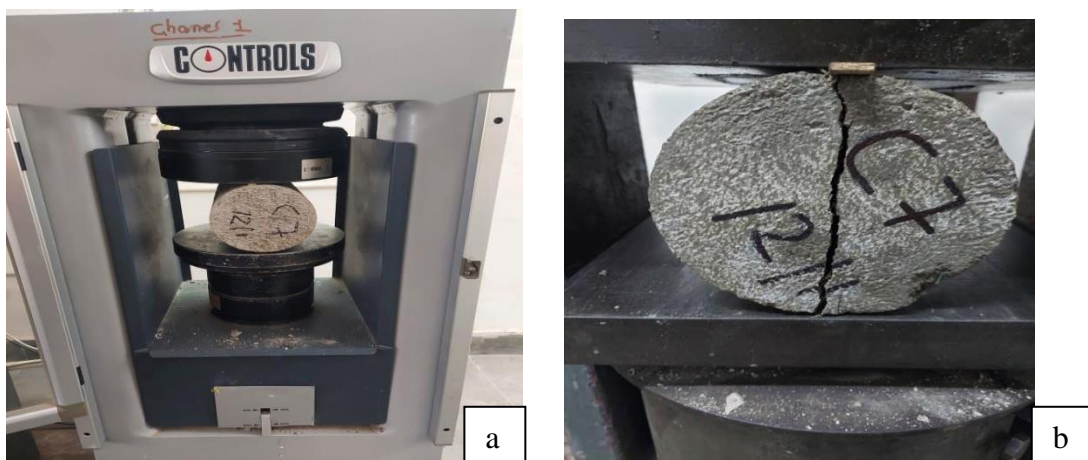


Figure 4.16 Split Tensile strength test on cylinder

The results of concrete mix with 100% cement are presented in Figure 4.17. The split tensile strength of E25, E50 & E100 mix had slight increase in strength compared to control mix i.e. E00 and whereas in E75 an increase of 40.61 % was seen. Since EAF slag aggregate has good mechanical properties compared to natural aggregate. The results of split tensile strength were in the same trend followed in compressive strength & flexural strength. E75 mix had achieved the highest split tensile strength among all the 5 mix's making 75 % EAF slag aggregate as the optimum replacement of natural aggregate. The strength achieved in E75 mix & E00 mix is comparable to results mentioned by (Rooholamini et al., 2019).

The results of concrete mix with 30% GGBFS replacement are presented in Figure 4.18. The split tensile strength of E25G30, E50G30, E75G30 & E100G30 mix had increase in strength compared to control mix i.e. E00G50 and the increase was of 58.86%, 29.76%, 31.11 & 27.08 respectively. E25G30 mix i.e. 25 % EAF slag aggregate replacement had highest strength among all the mix's, So 25% coarse EAF slag aggregate can be used as a with 30 % GGBFS.

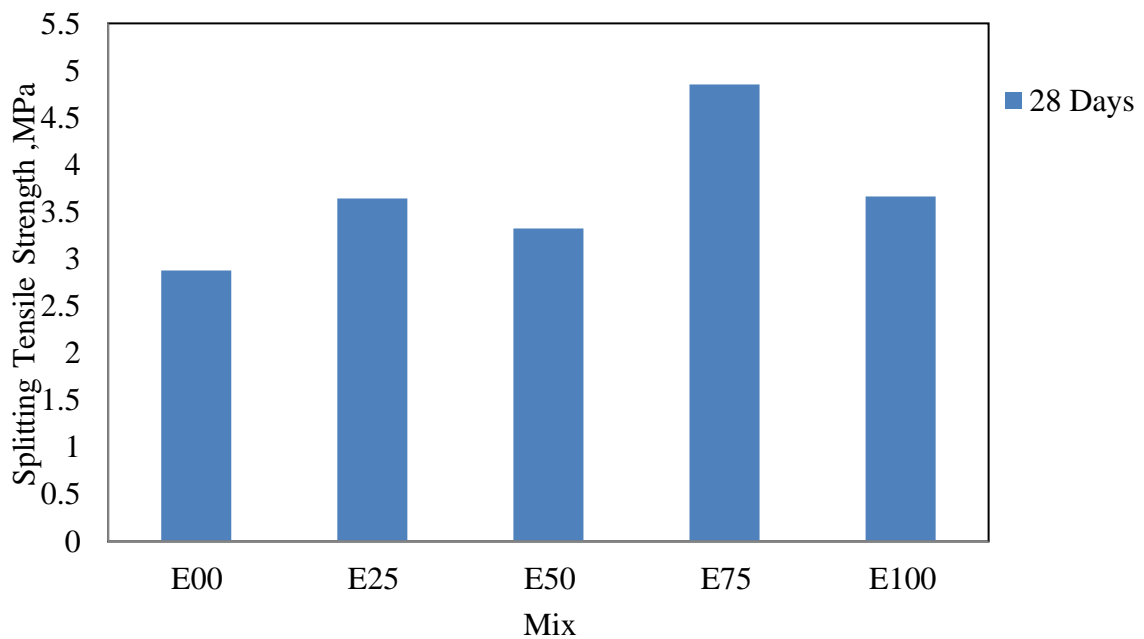


Figure 4.17 Split tensile strength on mix containing 100 % cement

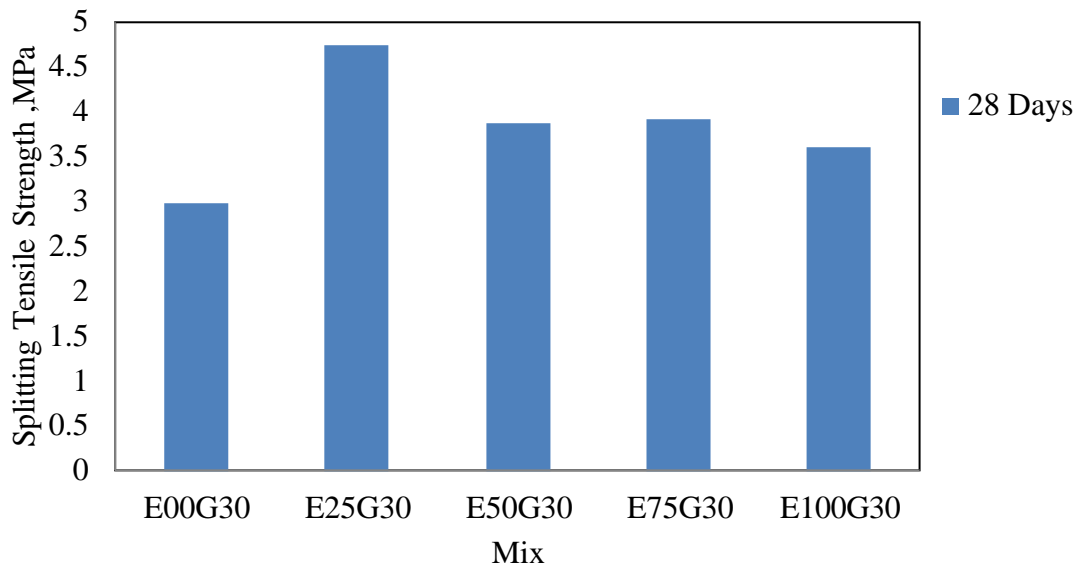


Figure 4.18 Split tensile strength on mix containing 30 % GGBFS

The results of concrete mix with 50% GGBFS replacement are presented in Figure 4.19. The split tensile strength of E25G50, E50G50, E75G50 & E100G50 mix had more strength compared to control mix i.e. E00G50. The trend seen in 50 % GGBFS mix's is similar to 30 % GGBFS mix's i.e the optimum percentage of EAF slag aggregate replacement is 25 %.

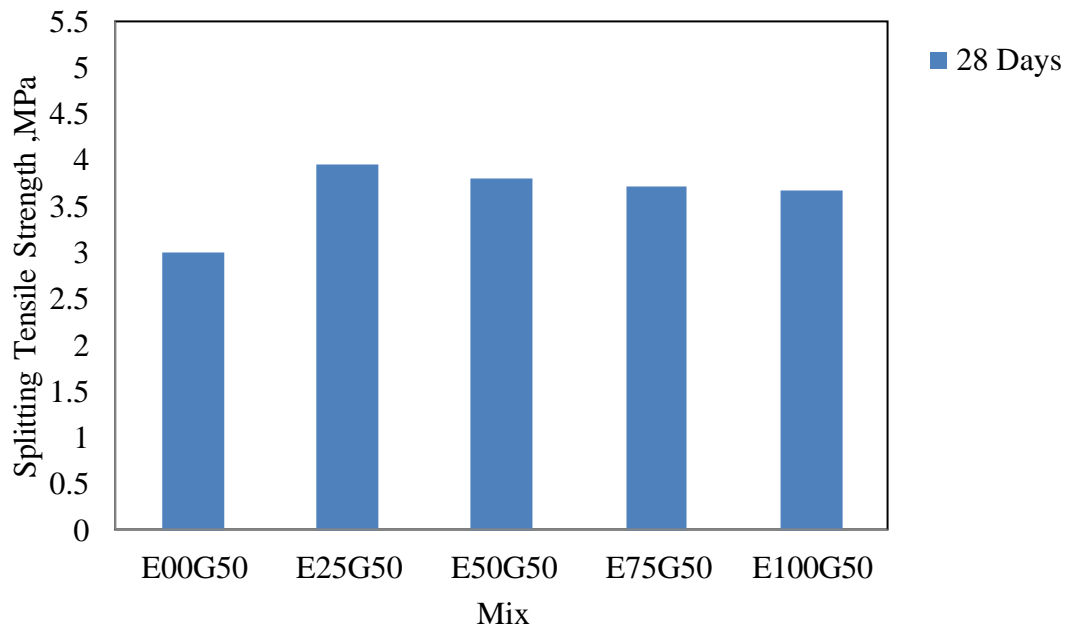


Figure 4.19 Split tensile strength on mix containing 50 % GGBFS

The results of concrete mix's with 70% GGBFS replacement are presented in Figure 4.20. The split tensile strength of E25G70, E50G70, E75G70 & E100G70 mix had increase in strength compared to control mix i.e. E00G70. The trend seen in Figure 4.20 is similar to the trend seen in compressive strength in Figure 4.9.

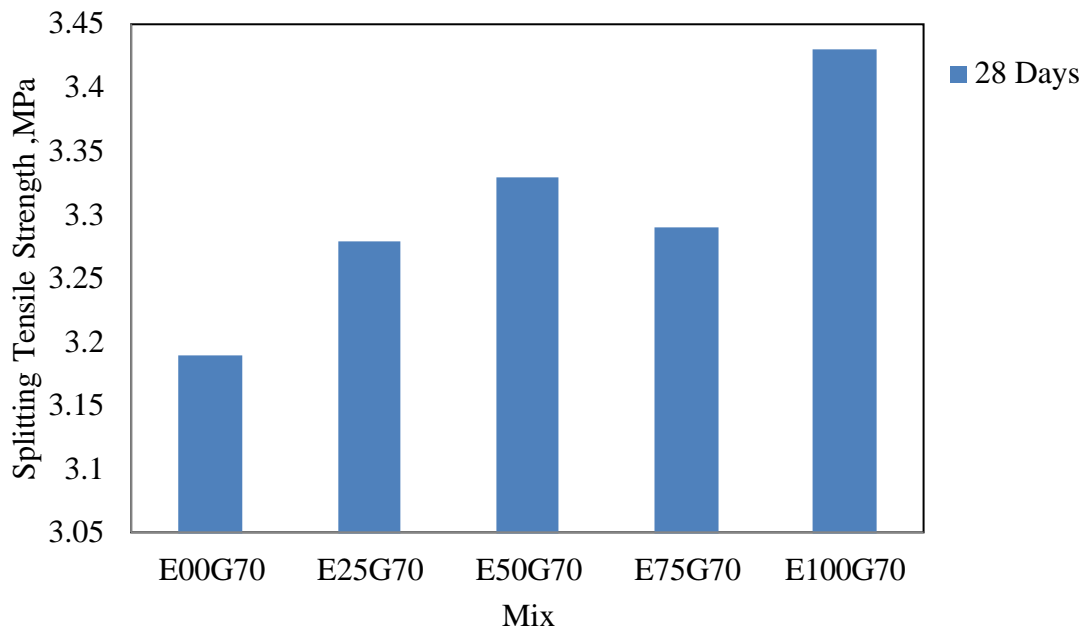


Figure 4.20 Split tensile strength on mix containing 70 % GGBFS

In all the mix's having different EAF slag aggregate percentage i.e. (25%,50%,75% &100%) were having split tensile strength more than their respective control mix's this may be due to rough texture characteristics of EAF slag aggregate and filling of the pores of aggregate by ettringite (M. Lam et al., 2018). A similar trend was seen in split tensile strength that was seen in compressive strength and flexure strength i.e. the strength increased with the increase in GGBFS percentage till 30 % GGBFS replacement for all the EAF slag aggregate replacement levels but further with increase in GGBFS percentage (50% &70%) the strength started reducing for all the EAF slag aggregate replacement levels. Fig. shows the failure pattern of the cylinder in split tensile and it can be seen that the mix containing different percentage of slag aggregate and GGBFS all were having same failure pattern as E00 mix. This tells that the concrete was uniformly compacted and during the test the load was uniformly distributed as the crack pattern is similar in all mixes.



E00



E25



E50



E75

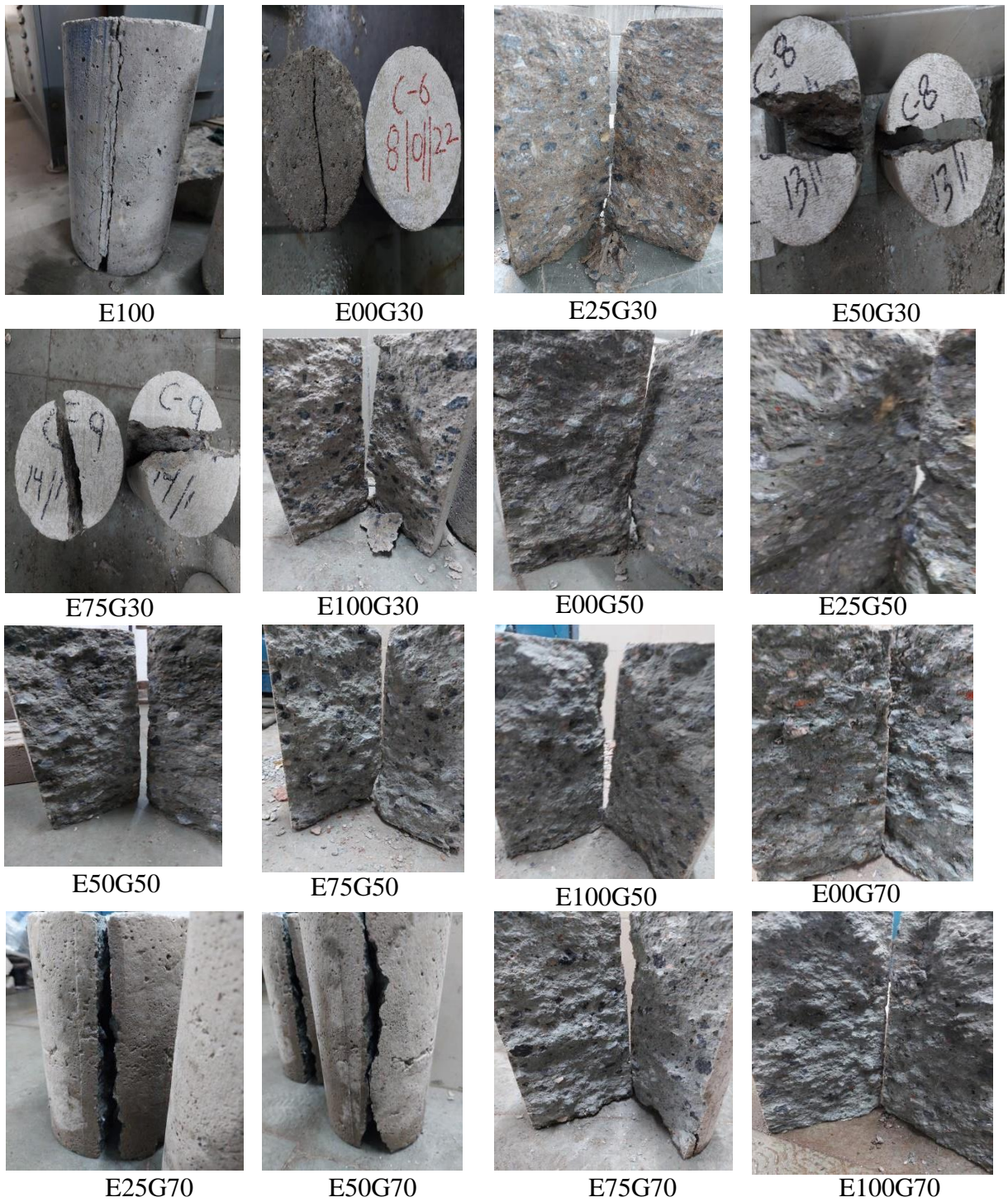


Figure 4.21 Failure pattern of cylinder during split tensile strength

4.4.4 Static Elastic Modulus

The elastic modulus test was done conforming to IS 516 on cylindrical specimen of 150 mm diameter and 300 mm height as shown in Figure 4.22 .The elastic modulus was calculated for 28 days cured specimen.

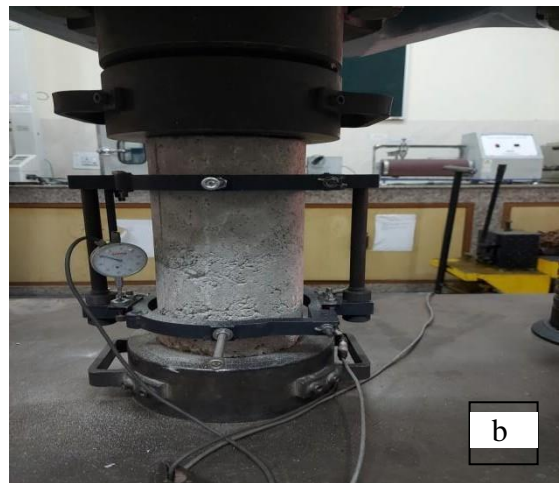


Figure 4.22 Testing for modulus of elasticity on cylinder

The results of elastic modulus is presented in Figure 4.23 .There was slight decrease in modulus value with the increase in EAF slag aggregate percentage compared to mix E00. But all the mix's i.e. E00,E50 & E100 were having modulus value more than 32 GPa. In 30 % GGBFS mix's with the increase in EAF slag aggregate percentage there was slight increase in modulus value compared to mix E00G30. The trend of 30 % GGBFS mixes were same as of other mechanical properties. Mixes with 30 % were having strength more than 32 GPa, so 100 EAF slag aggregate can be used with 30 % GGBFS cement replacement. In 50 % GGBFS mix's the modulus of elasticity decreased with increase in EAF slag aggregate percentage when compared to control mix E00G50, but all the with 50 % GGBFS mix were having strength more than 32 GPa, so 100% EAF slag aggregate can be used with 50 % GGBFS as cement replacement. Whereas the mix's having 70 % GGBFS had increase in modulus value with the increase in EAF slag aggregate replacement when compared to control mix E00G70 which was following the same trend as of other mechanical properties. The mix with 0 % & 50 % EAF slag aggregate with 70 % GGBFS as cement replacement cannot be used as the modulus value was less than 32 GPa but 100 % EAF slag aggregate with 70 % GGBFS was having modulus value more than 32 GPa which can be used. A same trend was noticed with the increase in GGBFS percentage till 30 % cement replacement the modulus value increased but further increase in GGBFS percentage (i.e. 50 % & 70 %) the modulus value decreased when compared to control mix E00,E50 & E100. But it was noticed that all the 12 mixes were having the modulus value more than the modulus value that we get using relation of compressive strength and modulus of elasticity.

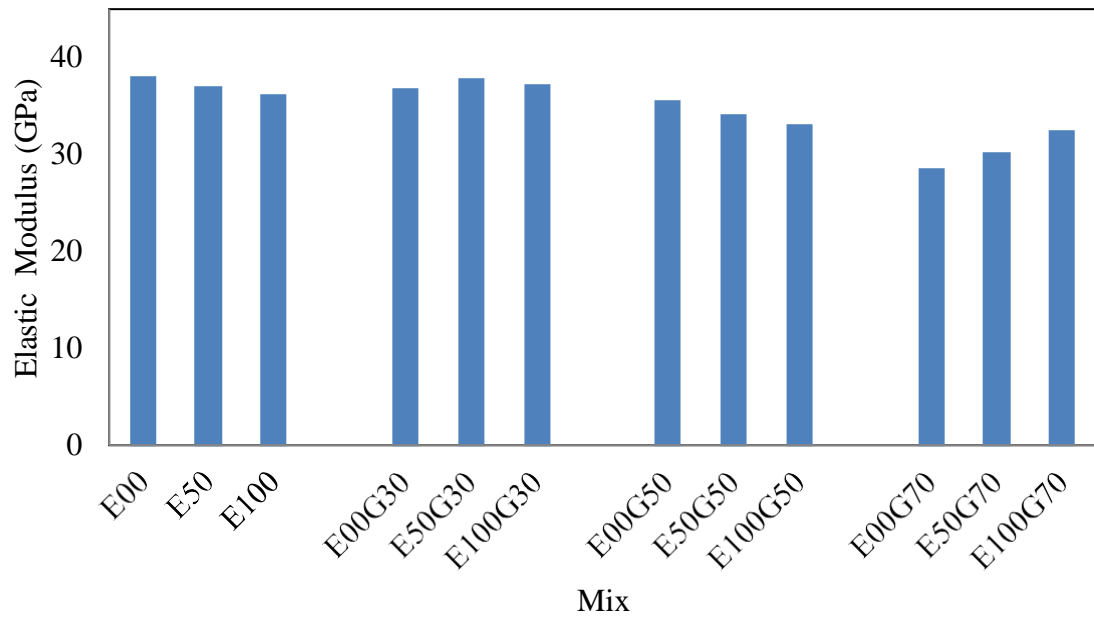


Figure 4.23 Modulus of elasticity

4.5 NON-DESTRUCTIVE TESTING

4.5.1 Ultrasonic Pulse Velocity

The quality of concrete i.e. its homogeneity, presence of imperfection and the dynamic modulus of elasticity can be found out using UPVIS 13311-1(1992).The UPV test was done conforming to IS 13311 on 150 mm cubes on 28th day. A PUNDIT UPV Tester (Proceq make) was used and the transducers used were having an operating frequency of 54 kHz. Direct transmission method was adopted as shown in Figure 4.24 .The pulse velocity was calculated from following equation.

$$V = L/T$$

Where,

L = Length of specimen

T= Transit Time



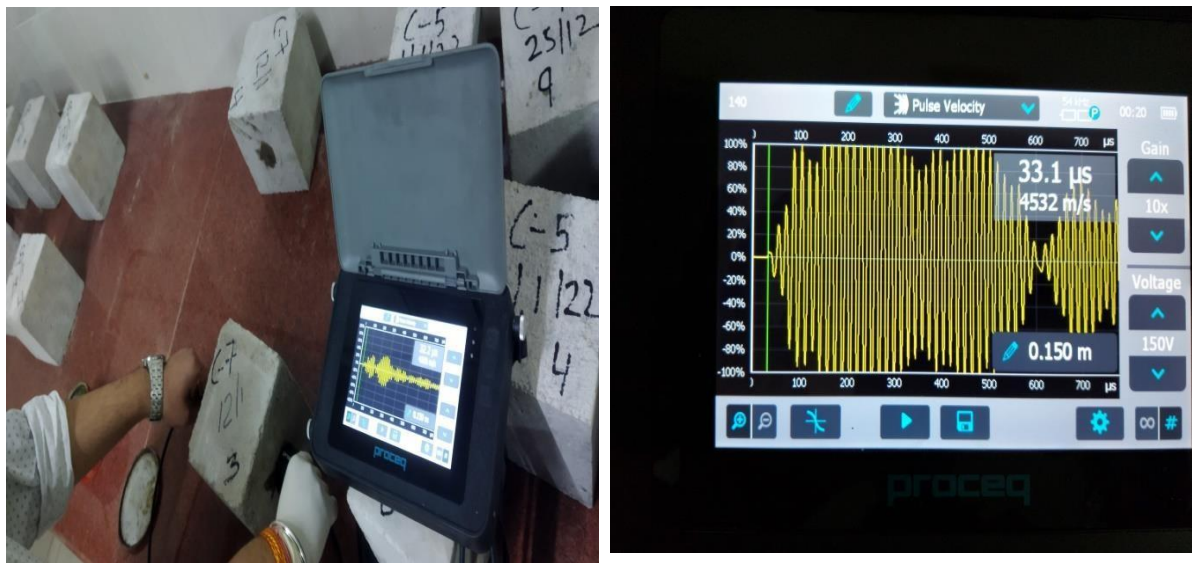


Figure 4.24 UPV Testing on cubes

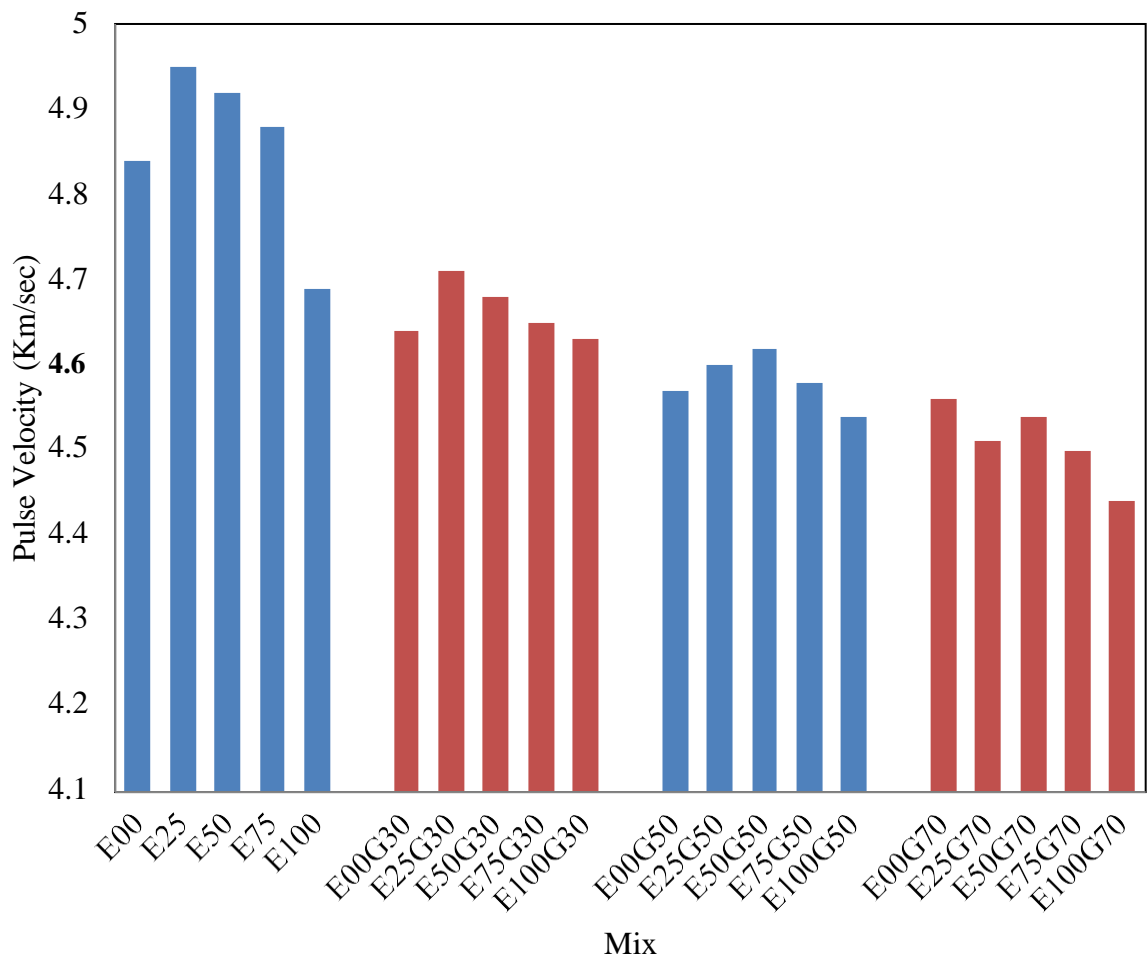


Figure 4.25 UPV

The Figure 4.25 presents the result of UPV test. In mixes with 100 % cement there was increase in pulse velocity with the increase in EAF slag aggregate percentage till 25 %

replacement of natural aggregate but with further increase in EAF slag aggregate percentage the pulse velocity decreased, this decrease may be due to the increase in voids of the concrete due to EAF slag aggregate. The mix's containing EAF slag aggregate (i.e. 25 %,50 % & 75 %) were having pulse velocity more than the control mix. But all the mix's containing 100 % cement were having pulse velocity in the range of 4.95-4.69 km/sec i.e. more than 4.5 km/sec indicating quality of concrete excellent. The mix's containing 30 % GGBFS ,50 % GGBFS and 70 % GGBFS as a replacement of cement showed the same trend as seen mix's containing 100 % cement. But with the increase in GGBFS percentage the pulse velocity decreased. Mix containing 30 % GGBFS with different percent of EAF slag aggregate were having pulse velocity in range of 4.71 – 4.63 km/sec. Mix containing 50% GGBFS with different percent of EAF slag aggregate were having pulse velocity in range of 4.62 – 4.54 km/sec. Mix containing 70% GGBFS with different percent of EAF slag aggregate were having pulse velocity in range of 4.56 – 4.44 km/sec. All the mix containing 30 % GGBFS, 50 % GGBFS and 70 % GGBFS were having pulse velocity more than 4.5 km/sec indicating excellent quality of concrete. Only mix containing 70 % GGBFS and 100 % EAF slag aggregate was having pulse velocity less than 4.5 km/ sec, but still it will come in good quality concrete.

4.5.2 Rebound Hammer

The rebound hammer test was done as per IS 13311-2 (1992) .Rebound hammer test is done to know about the quality & uniformity of concrete from its surface hardness. N-Type analogue Schmidt proceq made rebound hammer was used and specimen used for testing was 150 mm cube as shown in Figure 4.26. The load applied during testing was of 157.5 KN and the rebound number was noted. The test was done on 28 days specimen and average of 3 sample were taken. After recording the rebound number from the graph given on rebound hammer the compressive strength was found out.



Figure 4.26 (a) Rebound hammer testing on cube (b) Schmidt rebound hammer

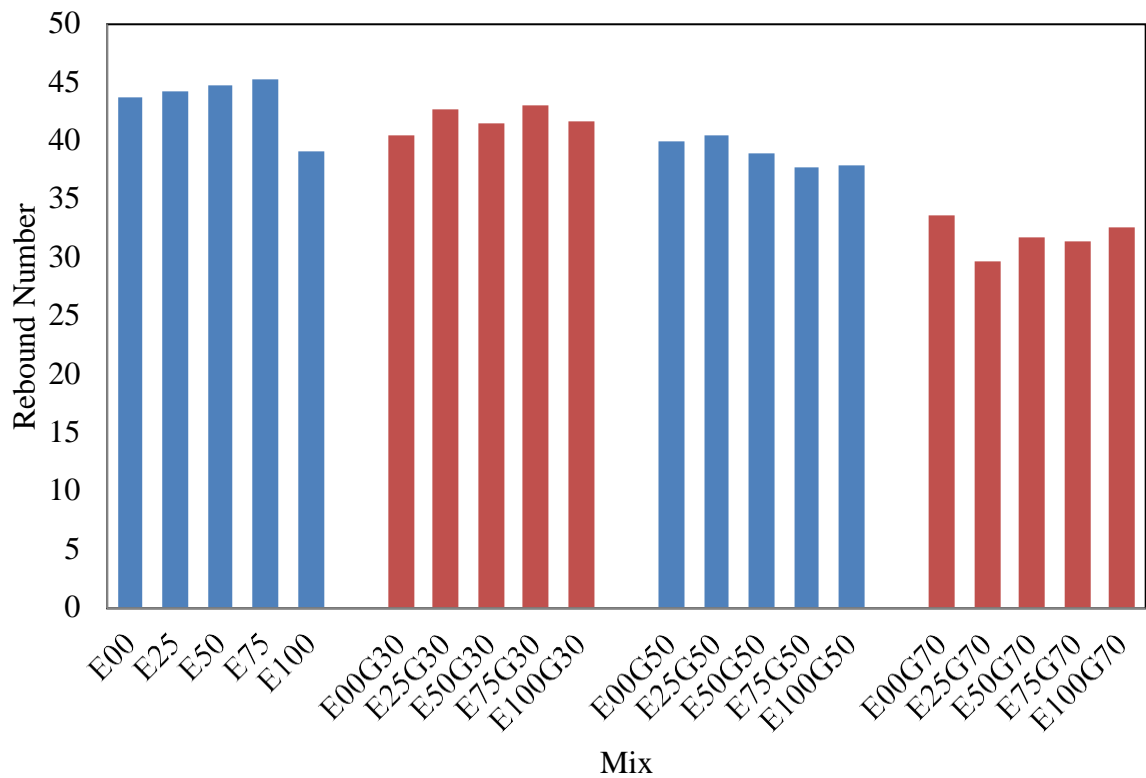


Figure 4.27 Rebound Hammer

The test results are presented in Figure 4.27. The mix with 100 % cement showed a increase in rebound number with the increase in EAF slag aggregate percentage but mix containing 100 % EAF slag aggregate showed drastic decrease in rebound number.100 % EAF slag aggregate showed less rebound number because of the increase in voids content in concrete when compared to control mix E00.Mix's containing 30 % GGBFS with different percentage of EAF slag aggregate were having rebound number more than there control mix E00G30.In mix with 50 % GGBFS with the increase in EAF slag aggregate percentage the rebound number decreased slightly when compared to control mix E00G50.Mix's containing 70 % GGBFS and 25% ,50 % ,75% & 100 % EAF slag aggregate replacement were having rebound number less than the control mix E00G70. With the increase in GGBFS percentage the rebound number decreased. A correlation was developed between the rebound number and the compressive strength found out from the graph and is given in Equation 4.5.The correlation developed was having R^2 value 0.9952.

$$y = 1.7252x - 26.59 \quad \text{Equation (4.5)}$$

The value of compressive strength got after testing cubes at 28 days were almost equal to compressive strength got from the rebound number.

4.6 DURABILITY PROPERTIES

4.6.1 Water Absorption

The water absorption test was done on 100 mm cube after 28 days curing the sample. The saturated surface dry weight of the cube was taken and the cube was kept in oven for 24 hours at $102 \pm 2^\circ\text{C}$ and then oven dried weight was recorded. In the mix's containing 100 % cement with the increase in EAF slag aggregate percentage the water absorption has increased and the percentage increase was 51.21 %,62.19%,78.04% &93.29 % when compared to mix E00.As EAF slag aggregates were more porous and having high water absorption as compared to natural aggregate there was increase in water absorption with the increase in EAF slag aggregate percentage in concrete. But the water absorption was less compared to results of (M. N.-T. Lam et al., 2018b). In 30 % GGBFS mix's there was decrease in water absorption with the increase in EAF slag aggregate percentage when compared to mix E00G30.This decrease in water absorption was due to filling of the pores of EAF slag aggregate as also said by (Siddique and Iqbal Khan, 2011).

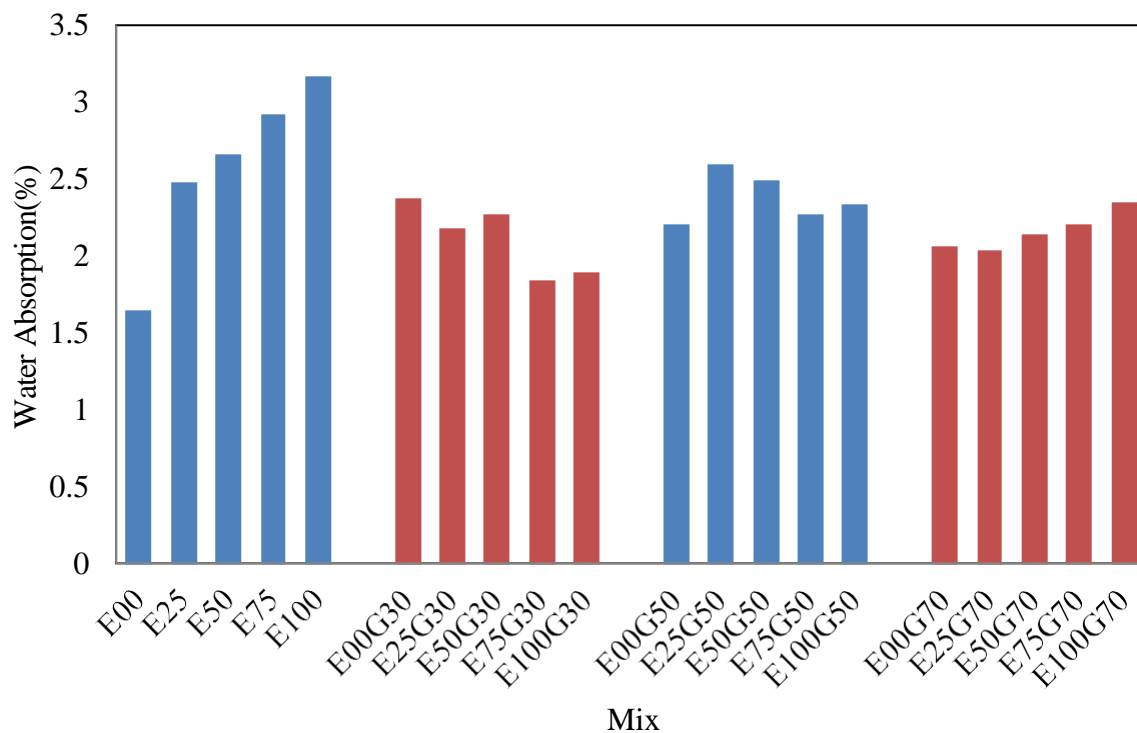


Figure 4.28 Water Absorption

But in the mix's containing 50 % & 70 % GGBFS with the increase in EAF slag aggregate percentage there was a increase in water absorption and the similar trend was seen in (Husein Bayqra et al., 2022; M. N.-T. Lam et al., 2018b).Overall when compared to mix's containing

100 % cement there was decrease in water absorption in 30 % GGBFS mix's ,50 % GGBFS mix's & 70 % GGBFS mix's. Least water absorption was of mix's containing 30 % GGBFS.

4.6.2 Abrasion Resistance

Deterioration of concrete pavement may occur due to abrasion by tyre pressure and the abrasive material carried by water during rainy season. Thus abrasion resistance of pavement is one of important measures in terms of durability. The abrasion resistance was done as per IS 9284 on 100 mm cubes after 28 days of curing and the abrasive charge used for test was silica sand as shown in Figure 4.29.



Figure 4.29 (a) Sand blasting machine ,(b) Ennore sand used ,(c) After abrasion of 1st surface of E00 mix

The mixes containing 100 % cement and different percentage of EAF slag aggregate had decrease in weight loss with the increase in EAF slag aggregate percentage when compared to control mix E00. Because EAF slag aggregate have good abrasion resistance as they are having less abrasion value as compared to natural aggregate as mentioned in section .In mix's containing 30 % GGBFS , 50 % GGBFS & 70 % GGBFS with different EAF slag aggregate percentage the same trend was seen as in mix's containing 100 % cement. But with the increase in GGBFS percentage in the mix the resistance to abrasion decreased. When mix E00G70 was compared with mix E00 the increase in weight loss was 32.57 % , this was because GGBFS concrete has late gain of strength and GGBFS is less denser as compared to cement. But all mix's having 100 % EAF slag aggregate were having less weight loss as compared to their respective control mix. Only mix containing 30 % GGBFS with 100 % EAF slag aggregate was having least weight loss as compared to other 19 mix's.

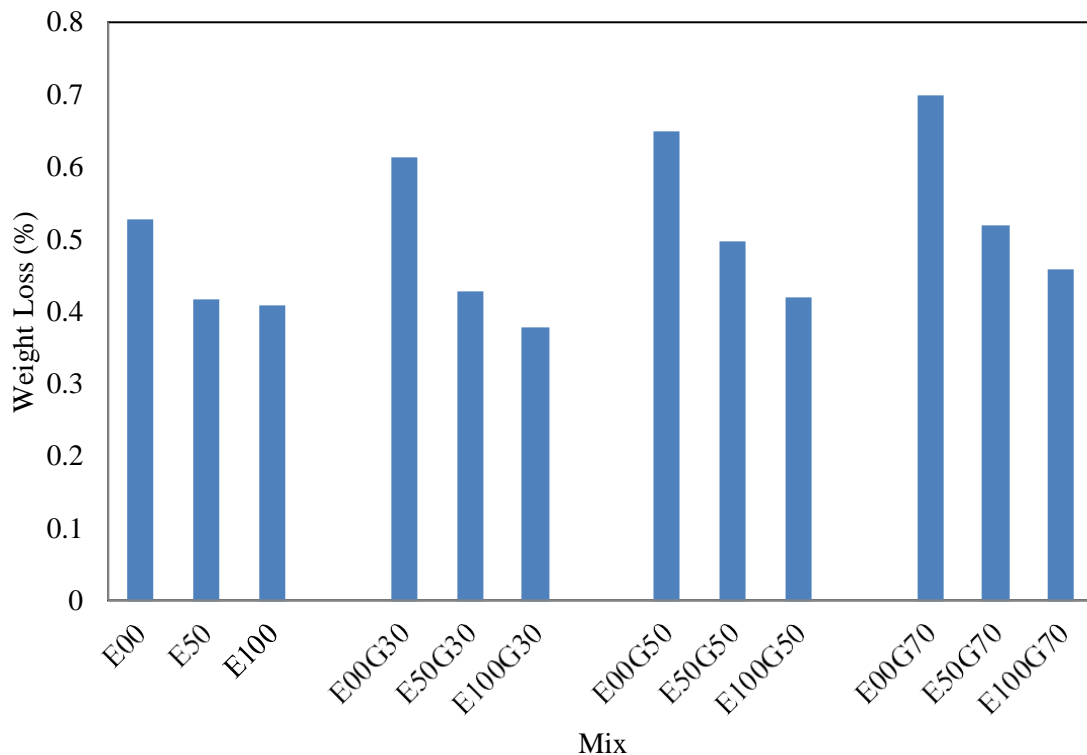


Figure 4.30 Abrasion Resistance

4.6.3 Skid Resistance

The skid resistance of the concrete slabs were measured using british pendulum test (BPT). BPT is used to measure the surface microstructure indirectly. The BPT was done as per ASTM E303 – 93 (2018) as shown in Figure 4.31. The test was done on slab of size 500 mm * 500 mm * 100 mm and the test was done for both the surface condition dry as well as wet.

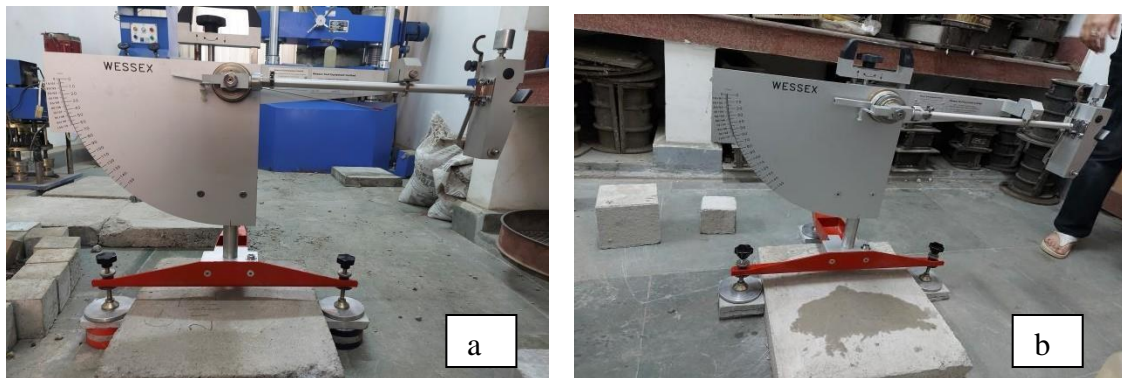


Figure 4.31 Apparatus for skid resistance (a) Dry surface (b) Wet Surface

The results of mix containing 100 % cement and different percentage of EAF slag aggregate are shown in Figure 4.32 .In mix E00 to E100 there was increase in skid resistance with the increase in EAF slag aggregate percentage in dry as well as wet surface when compared to control mix E00.Because EAF slag aggregate have rough surface texture & good resistance against weathering as compared to natural aggregate(Aziz et al., 2014).As al the 5 mix's of

100 % cement were having british pendulum number more than 65 the surface exhibited good to excellent skid resistance in all conditions of road which was conforming to IRC SP 83 (2018) hence 100 % slag aggregate can be used.

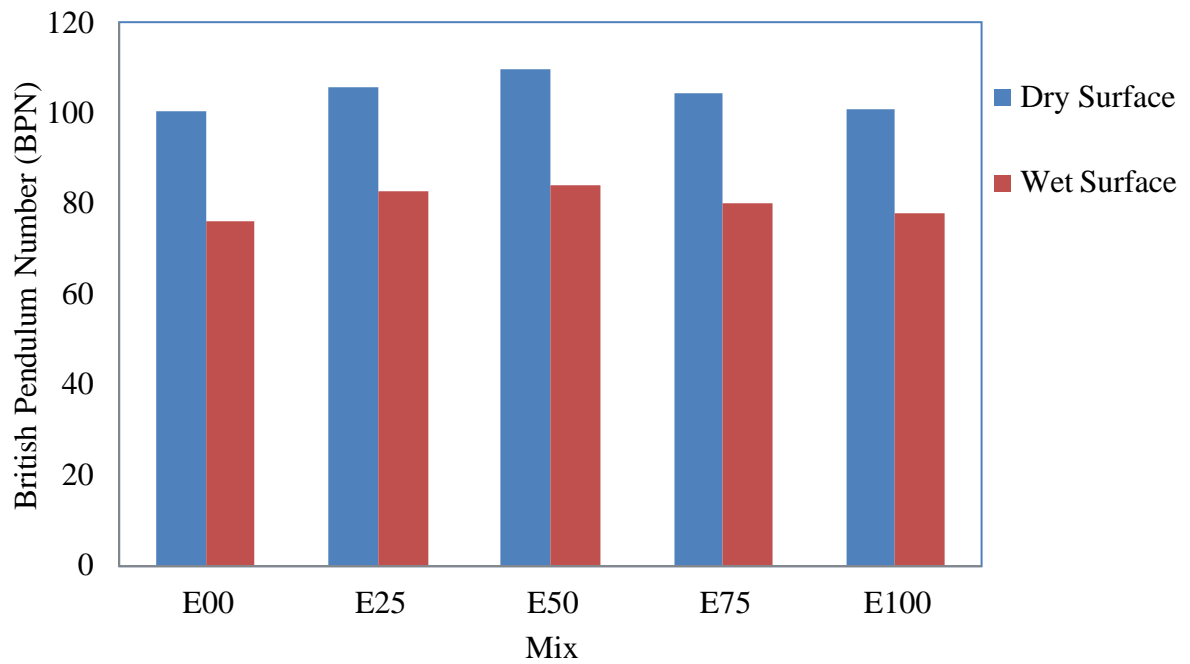


Figure 4.32 Skid resistance for mix containing 100 % cement

The results of mix containing 30 % GGBFS are given in Figure 4.33 .The same trend was seen in mix's containing 30 % GGBFS as seen in mix's containing 100 % cement with increase in slag aggregate percentage the resistance to skid increased. There was slight decrease in skid resistance when mix E75G30 was compared to mix E100G30.

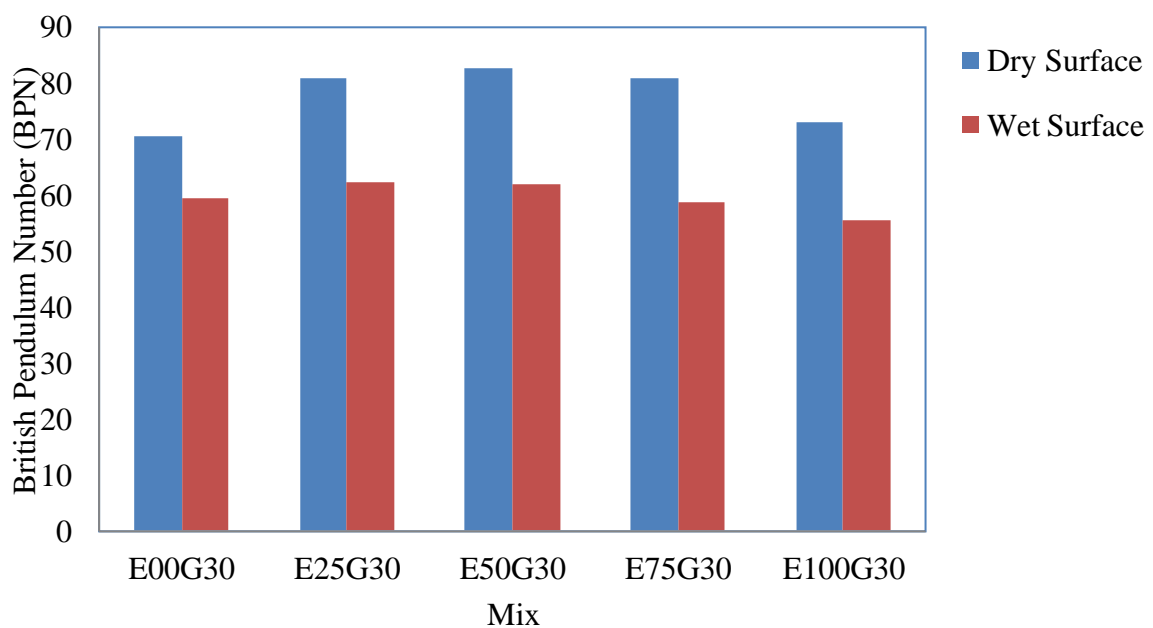


Figure 4.33 Skid resistance for mix containing 30 % GGBFS

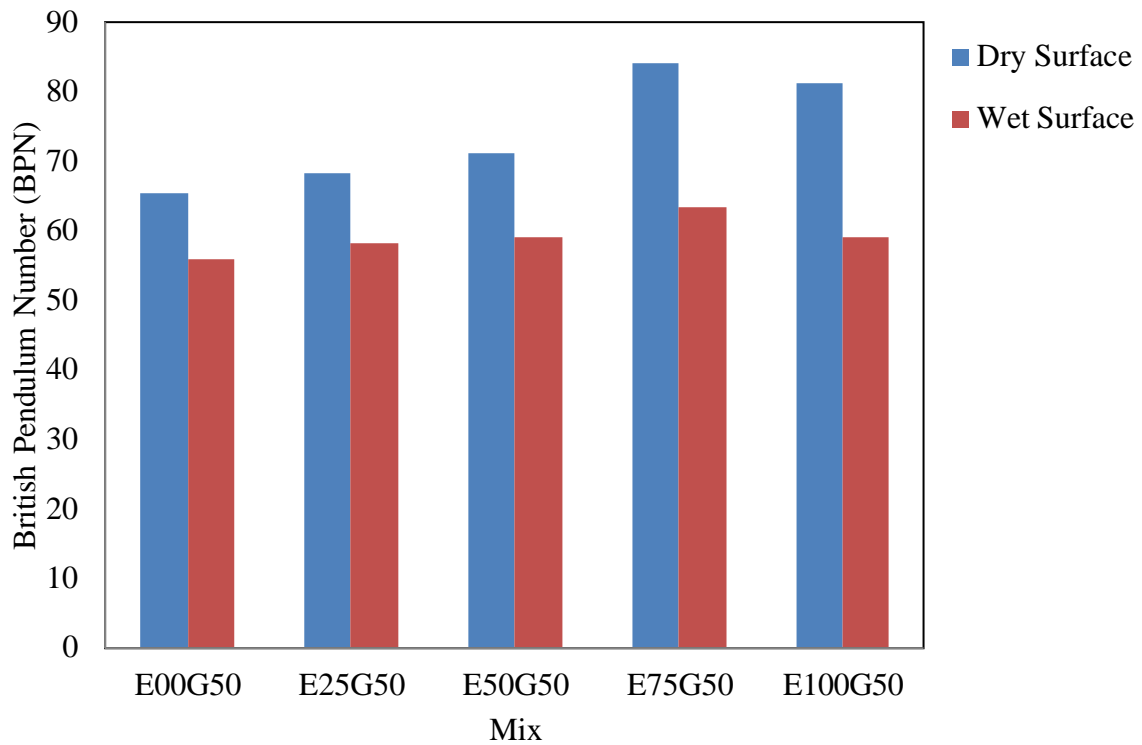


Figure 4.34 Skid resistance for mix containing 50 % GGBFS

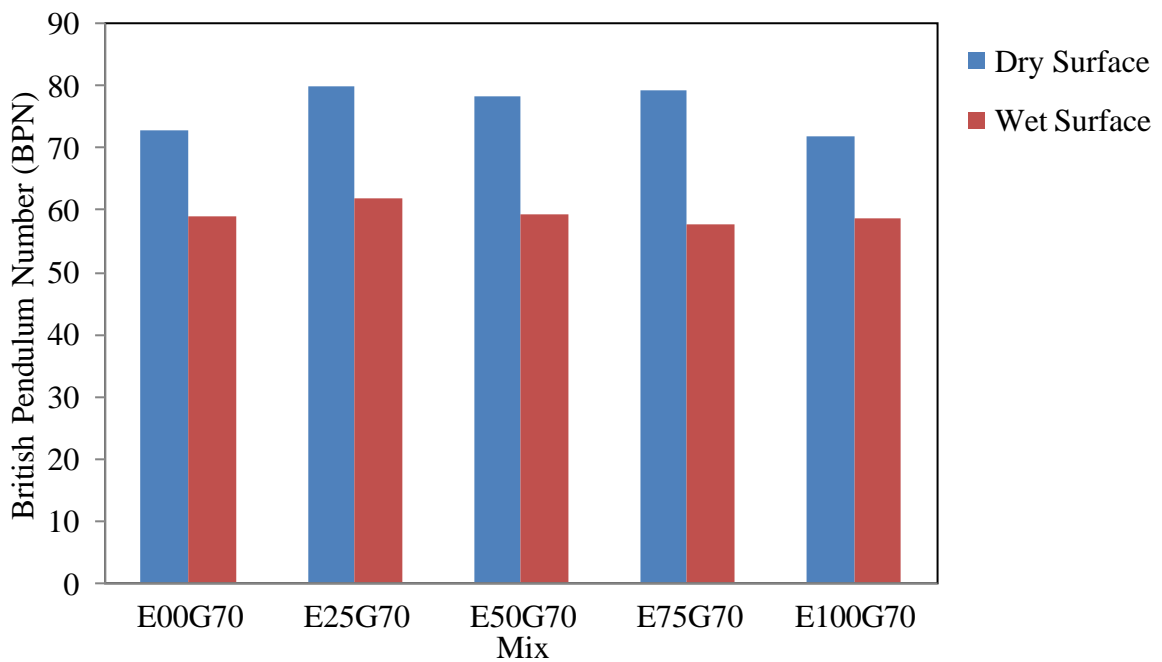


Figure 4.35 Skid resistance for mix containing 70 % GGBFS

BUT all the 5 mixes of 30 % GGBFS were having British pendulum number more than 55 the surface exhibited acceptable skid resistance in all conditions of road which was conforming to IRC SP 83 (2018) hence 100 % slag aggregate can be used with 30 % GGBFS as cement replacement.

The results of mixes containing 50 % GGBFS & 70% GGBFS are given in Figure 4.34 & Figure 4.35 respectively. The same trend was seen in mix's containing 50 % GGBFS & 70 % GGBFS as seen in mix's containing 100 % cement i.e. with increase in slag aggregate percentage the resistance to skid increased. In mix's containing 50 % GGBFS the mix E75G50 offered highest resistance to skid whereas in mix's containing 70 % GGBFS the mix E25G70 offered highest resistance to skid. But with the replacement of cement with GGBFS partially there was decrease in resistance to skid this was because of GGBFS improved the microstructure of cement paste and hence improved the quality of concrete in terms of surface levelling and hence the friction reduced. BUT mix's containing 50 % & 70 % GGBFS were having british pendulum number more than 55 hence the surface exhibited acceptable skid resistance in all conditions of road which was conforming to IRC SP 83 (2018) hence 100 % slag aggregate can be used with 50 & 70 % GGBFS as cement replacement.

4.6.4 Carbonation

The alkaline behaviour of concrete can be altered by carbonation. In natural carbonation the carbon dioxide present in atmosphere diffuses in concrete matrix and reacts with water forming carbonic acid and later react with cement forming CaCO_3 . The carbonation test was done as per IS 516 (Part 5 /section 3) :2021. The test was done on cube samples after taking 28 days compressive strength. Phenolphthalein was sprayed on the surface immediately after testing the cube. The test was done for mix containing 100 % cement and slag aggregate percentage being 0 %, 25 % ,50 % ,75 % & 100 % i.e E00,E25,E50,E75 & E100 mix and the results are shown in Figure 4.36. It was seen that completely the colour changed to dark pink colour and no surface was left where colour change was not there in control mix E00. In mix containing different percentage of slag aggregate the carbonation depth was less than 1mm that cannot be measured on scale and were in line with the results of (González-Ortega et al., 2019). This was because of slag aggregates were stabilized by ageing method by stock piling it due to which CO_2 diffusion is reduced by action of higher humidity and rain exposure (González-Ortega et al.,2019). Because of which 100 % slag aggregate can be used as the carbonation depth is negligible.



Figure 4.36 Carbonation of mix E75

4.6.5 Effect of hot water curing

As per ASTM D 4792 methodology a test was done to see the effect of expansive compounds i.e. CaO and MgO present in EAF slag aggregate on volumetric expansion of concrete causing surface cracking under hot water curing condition. For which the cube specimen of 100 mm size were kept in accelerated curing tank at 72°C for 14 days as shown in Figure 4.38. In all the 20 mix's there was no volumetric expansion causing cracking of concrete. In concrete containing limestone and gypsum more expansion was seen as compared to a concrete containing natural aggregate and blast furnace slag cement (Zulu et al., 2020). This was because the EAF slag aggregates were stabilized by aging method and hence the free lime and magnesium oxide present was utilised in forming a calcite layer on concrete surface. Hence 100 % slag aggregate can be used with 70 % GGBFS replacement as per this test.





Figure 4.37 Hot water curing

4.7 SUMMARY

In this chapter the experimental study was carried out to study the fresh properties, mechanical properties & durability properties of RCCP. From the results it was found that there was increase in the fresh density of concrete and also slight increase in the vebe time with the increase in slag aggregate percentage but increase in GGBFS percentage the vebe time decreased and the fresh density was comparable to upto 30 % GGBFS replacement and then decreased with the increase in GGBFS percentage. The mechanical strength properties increased with the increase in slag aggregate percentage in concrete when compared to mix E00 due to triple mixing. But with the increase in GGBFS replacement there was slight increase in mechanical properties upto 30 % GGBFS replacement and for 50 % GGBFS replacements the results were comparable but with 70 % GGBFS replacement there was tremendous decrease when compared to 100 % cement concrete. In UPV test and rebound hammer test all the mixes showed excellent quality of concrete. With the increase in slag aggregate percentage in concrete there was increase in water absorption, skid resistance and abrasion resistance but with the increase in GGBFS percentage the skid resistance, water absorption and abrasion resistance decreased when compared to 100 % cement concrete. The carbonation and hot water curing had negligible effect on RCCP containing EAF slag aggregate and with the increase in GGBFS replacement also there was no effect.

CHAPTER 5

CONCLUSION

5.1 OVERVIEW

The detailed experimental investigation was carried out to understand the structural properties of RCCP containing coarse EAF slag aggregate as replacement of natural coarse aggregate and partial replacement of cement with GGBFS which was compared to 100 % natural aggregate RCCP containing 100 % cement and partial replacement of cement with GGBFS, so that the formers use in RCCP can be determined. It starts with the stabilization of EAF slag aggregate, constituent material characterization and mix design. The combined gradation was done as per IRC SP 68 for each replacement of natural aggregate with coarse EAF slag aggregate to get a dense matrix of concrete. For five different replacement of EAF slag aggregate (i.e. 0% , 25% , 50% ,75% & 100%) and four different replacement levels of GGBFS (0%,30%,50% &70 %) the total number of mixes were 20. For all the 20 mixes the modified proctor test was done to determine the water content used for mix design and more than 100 proctor moulds were made to do this. The mix proportioning was done as per ACI 211. 3R and triple mixing process was adopted to get a proper bonding between aggregate and cement paste. The compaction in the mould was done using vibratory hammer and the compaction plates were fabricated according to the specimen casted. Various specimens were casted for mechanical and durability test. For each mix of casting 28 specimens were casted and total 560 specimens were casted. The specimens casted were tested at 7 and 28 days according to tests. Based on this study the conclusions are suggestion for future study has been proposed.

5.2 CONCLUDING REMARKS AND DISCUSSION

Based on the experimental study carried out on RCCP containing coarse EAF slag aggregate and GGBFS the following conclusions were drawn:

1. The volumetric expansion of EAF slag aggregate was less than 1.5% as it was stabilized by aging method and hence it was having a thin layer of calcite on it as the expansive compounds present in aggregate were utilized.
2. The specific gravity of cement and GGBFS were conforming to their respective IS codes.

3. The specific gravity & bulk density of EAF slag aggregate were 17.95 % & 15.20 % respectively more than natural aggregate and the water absorption of EAF slag aggregate were 6.45 times as compared to natural aggregate.
4. The mechanical properties of EAF slag aggregate were more as compared to natural aggregates. As the abrasion resistance, crushing value & impact value were 93.52 % ,29.36% & 56.36 % respectively more as compared to natural aggregates.
5. The single size gradation for 10 mm, 20mm natural aggregate were within the limits as specified by IS 383. The single size gradation for 20mm EAF slag aggregate was within the limits as specified by IS 383 but not for 10mm aggregate. When combined gradation was done for 0%,25 % ,50 %,75 % & 100 % slag aggregate replacement all the gradation were within the limits as specified in IRC SP 68 (2005) and the gradation curve were coinciding with the mid limit gradation curve.
6. The modified proctor test was done to get the water content for mix design and the water content was in the range of 5.5 % - 8 % for all the mixes. The cement used was 18.5 % and these values were conforming to IRC SP 68 and ACI 211.3R.
7. With the increase in slag aggregate replacement percentage the density of concrete increased when compared to E00 mix containing 100 % cement. With the increase in GGBFS percentage in concrete containing slag aggregate the density increased upto 30 % GGBFS replacement but with further increase in GGBFS the density started decreasing when compared to concrete containing 100 % cement with different percentage of slag aggregate.
8. In modified vebe test with the increase in slag aggregate replacement percentage the vebe time of concrete increased compared to E00 mix containing 100 % cement. With the increase in GGBFS percentage in concrete containing slag aggregate the vebe time reduced when compared to concrete containing 100 % cement with different percentage of slag aggregate.
9. With the increase in slag aggregate percentage there was increase in compressive strength and all the mixes containing 100 % cement and different percentage of slag aggregate were having compressive strength more than 40 MPa. The mix containing 30 % and 50 % GGBFS with different percentage of slag aggregate were having strength more than 40 MPa but a slight decrease in strength was there when compared to 100 % cement concrete. There was tremendous decrease in strength in mix containing 70 % GGBFS replacement and the strength was less than 40 MPa. Hence 50 % GGBFS can be used with 100 % slag aggregate replacement.

10. With the increase in slag aggregate percentage there was increase in flexure strength and upto 30 % GGBFS replacement the strength was comparable to 100 % cement mix but with the increase in GGBFS replacement the strength started decreasing. But all the mix containing 100 % cement, 30 % GGBFS, 50 % GGBFS & 70 % GGBFS with different percentage of slag aggregate were having flexural strength more than 4.95 MPa.
11. In split tensile strength the mix containing different percentage of slag aggregate were having strength more than the respective control mix and with the increase in GGBFS percentage there was a decrease in strength when compared to 100 % cement concrete.
12. The elastic modulus decreased slightly with the increase in slag aggregate percentage in mix containing 100 % cement and 50 % GGBFS whereas opposite trend was seen in mix containing 30 % GGBFS and 70 % GGBFS. The same trend was seen upto 30 % GGBFS replacement the elastic modulus was comparable and with increase in GGBFS percentage further the elastic modulus started decreasing. But all the mix were having elastic modulus more than 32 GPa except the mix containing 70 % GGBFS and 50 % EAF slag aggregate.
13. All the 20 mixes were having excellent quality of concrete as the pulse velocity was more than 4.5 km/sec and the rebound number depicted the same compressive strength as got during the compression testing.
14. The water absorption increased with increase in slag aggregate percentage in 100 % cement concrete whereas with the increase in GGBFS percentage there was decrease in water absorption.
15. Skid resistance & abrasion resistance increased with increase in slag aggregate percentage in 100 % cement concrete whereas with the increase in GGBFS percentage there was decrease in skid resistance & abrasion resistance.
16. The effect of carbonation and hot water curing was negligible on the RCCP containing different percentage of slag aggregate with cement and GGBFS replacement.
17. From the study it was found that 50 % GGBFS can be replaced with cement and 100 % coarse EAF slag aggregate can be replaced with natural coarse aggregate as all the mechanical & durability for mix E100G50 was comparable or more than the control mix E00.

5.3 SUGGESTION FOR FUTURE WORK

From the above study it can be said that the mechanical and durability properties of concrete improves with the increase in slag aggregate percentage upto certain limit but with the use of GGBFS these properties decreases and only improvement seen is in water absorption. But some more durability test and microstructural analysis should be done as the physical and mechanical properties of EAF slag aggregate completely depends on the furnace type and condition as well as the quality of steel produced and the stabilization method used further to utilise the expansive compounds present in slag aggregate. With due consideration to this the future work proposed is:

1. Study of microstructural analysis of RCCP containing coarse EAF slag aggregate and GGBFS.
2. Study of durability properties such as sulphate resistance, freeze and thaw & acid attack in RCCP containing coarse EAF slag aggregate and GGBFS.
3. Study of RCCP containing coarse EAF slag aggregates from different steel industry.
4. Study of RCCP containing coarse EAF slag aggregates stabilised by carbonation method.
5. Studies of RCCP containing fine EAF slag aggregate and coarse EAF slag aggregates with GGBFS.

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APPENDIX

INDEX

LIST OF PUBLICATION

EXPERIMENTAL INVESTIGATION ON USE OF COARSE EAF SLAG AGGREGATE AND GGBFS IN ROLLER COMPACTED CONCRETE PAVEMENT

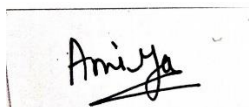
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