PRODUCTION OF HIGH STRENGTH AND DURABLE CONCRETE USING INDUSTRIAL BY-PRODUCTS

A thesis submitted in partial fulfillment of the requirements for the award of the degree of

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Submitted by

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CERTIFICATE

This is to certify that the work which is being presented in this thesis report entitled, "**PRODUCTION OF HIGH STRENGTH AND DURABLE CONCRETE USING INDUSTRIAL BY-PRODUCTS**" being submitted by "**Mr. ANKIT KUMAR JAIN, Registration no.-801081005**", in partial fulfilment of the requirements for the award of degree of **Master of Engineering (CAD/CAM & Robotics)** at **Thapar University, Patiala** is a bonafide work carried out by him under our guidance during July 2011 to June 2012. The matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any other degree.

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ABSTRACT

In the today's construction scenario there is a acute shortage of fine aggregate (sand) as well as cement production is highly energy intensive, costly and affects the environment. The present study has been done to find the optimal usage of industrial by-products (Blast furnace slag, Ladle furnace slag, Fly-ash, Electric arc furnace slag, Glass powder and Steel powder/Scrap) as substitutes to cement and aggregates.

The present work aimed to study the effect of different input parameters, namely water to cement ratio, by-product percentage used as a binder, by-product percentage used as a fine-aggregate, type of by-product used as a binder, type of by-product used as a fine-aggregate and curing time on output responses, namely compressive strength, splitting tensile strength and water penetration depth.

The effect of various input parameters on output responses have been analyzed using Analysis of Variance (ANOVA) and followed by optimization of the process parameters. Main effect plot has been used to determine the optimal design for each output parameters.

NOMENCLATURE

GGBFS	:	Ground Granulated Blast Furnace Slag
LFS	:	Ladle Furnace Slag
FA	:	Fly-Ash
GP	:	Glass Powder
EAFS	:	Electric Arc Furnace Slag
SP	:	Steel Powder
Dof	:	Degree of Freedom
ANNOVA	:	Analysis of Variance
DOE	:	Design of Experiment
SEM	:	Scanning Electron Microscopy
EDAX	:	Energy Dispersive X-ray Spectroscopy
S/N	:	Signal to Noise
OA	:	Orthogonal Array

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CHAPTER 1 INTRODUCTION

1.0 GENERAL

Concrete is a composite construction material, composed of cement (commonly Portland cement), aggregates (generally a coarse aggregate made of gravel or crushed rocks such as limestone, granite plus a fine aggregate such as sand), water and chemical admixtures.

Production of Portland cement involves the grinding of raw materials, the calcinations of raw materials at 1500°C and the grinding of cement clinker and gypsum. It is an energy-intensive process and requires approximately 4000 MJ of energy per ton of cement. Properly fast cooled iron blast furnace slag, steel slag, phosphorus slag, copper slag and lead slag have cementitious or pozzolanic properties. Because the use of these slags as cementing components needs only grinding, it will save substantial amount of energy required for production of Portland cement. For example, the energy required to grind granulated blast furnace slag is approximately only 10% of the total energy required for the production of Portland cement [32]. A partial replacement of cement by mineral admixtures, such as, fly ash, ground granulated blast furnace slag (GGBS), silica fume, metakaolin, rice husk ash or fillers such as limestone powders in concrete mixes would help to overcome these problems and lead to improvement in durability of concrete as well [11]. The chemical composition and physical properties of Portland cement are given in Table 1.1 & Table 1.2.

Cement basically contains limestone which on reaction with water releases carbon dioxide [43]. Carbon dioxide being a greenhouse gas is harmful for the environment. The greenhouse effect is a process by which thermal radiation from a planetary surface is absorbed by atmospheric greenhouse gases, and is re-radiated in all directions. Since part of this re-radiation is directed back towards the surface, energy is transferred to the surface and the lower atmosphere. As a result, the temperature there is higher than it would be, if direct heating by solar radiation were the only warming mechanism as shown in figure 1.1. The world's yearly cement production of 1.6 billion tons account for about 7% of global loading of CO_2 into the atmosphere.

Portland cement, the principal cement in use today is the one responsible for the release of a large amount of green house gases. Producing a ton of Portland cement requires about 4GJ of energy and Portland cement clinker manufacture releases approximately 1 ton of CO_2 into the atmosphere [52].

Portland cement was found to be the primary source of CO_2 emissions generated by typical commercially produced concrete mixes, being responsible for 74% to 81% of total CO_2 emissions. The next major source of CO_2 emissions in concrete was found to be coarse aggregate, being responsible for 13% to 20% of total CO_2 emissions [52].

Even the cost of production of cement is quite high as compared to other replacements such as fly ash, slag etc. Portland fly ash cement contains up to 30 % fly ash. The fly ash is pozzolanic, so that ultimate strength is maintained. Because fly ash addition allows lower concrete water content, early strength can also be maintained. Where good quality cheap fly ash is available, this can be an economic alternative to ordinary Portland cement [9].

Mining of limestone is also quite hazardous to the environment. This leads to destruction of various landscapes. Soil texture at places near the mines is poorly affected due to the processes used in mining. This leads to natural hazards such as landslides etc. Hence, replacements for cement with alternative materials have become more of a rule than a choice. Fly ash and some kinds of slags are known to show pozzolanic properties and hence are used as partial replacements for cement which is used as a binder in concrete [22].

Aggregates are inert granular materials such as sand, gravel, or crushed limestone that, along with water and Portland cement, are an essential ingredient in concrete. For a good concrete mix, aggregates need to be clean, hard, strong particles free of absorbed chemicals or coatings of clay and other fine materials that could cause the deterioration of concrete [3]. Aggregates, which account for 60 to 75 percent of the total volume of concrete, are divided into two distinct categories-fines and coarse. Fine aggregates generally consist of natural sand or crushed stone with most particles passing through a less than 3/8-inch (0.075 to 0.425mm) sieve. Coarse aggregates are any particles greater than 0.19 inch (4.75 mm), but generally range between 3/8 and 1.5 inches (9.5 mm to 37.5 mm) in diameter. Gravels constitute the majority of coarse aggregate used in concrete with crushed stone making up most of the remainder.

Natural gravel and sand are usually dug or dredged from a pit, river, lake, or seabed. Crushed aggregate is produced by crushing quarry rock, boulders, cobbles, or large-size gravel. Aggregate processing consists of crushing, screening, and washing the aggregate to obtain proper cleanliness and gradation. If necessary, a benefaction process such as jigging or heavy media separation can be used to upgrade the quality.

The industrial slags, which have cementitious or pozzolanic properties, should be used as partial or full replacement for Portland cement rather than as bulk aggregates or ballasts because of the high cost of Portland cement, which is attributable to the high energy consumption for the production of Portland cement.

1.1 WHY INDUSTRIAL BY-PRODUCT IN CONCRETE?

A by-product is a secondary product derived from a manufacturing process, chemical reaction etc. A by-product can be useful and marketable or it can be considered a waste.

Large quantities of by-products are generated from manufacturing processes & industries. As a result solid waste management has become one of major environmental concerns in the world [55]. With an increasing awareness about the environment, scarcity of land-fill space and due to its ever increasing cost by- product utilization has become an attractive alternate to disposal. High consumption of natural resources, high amount of production of industrial waste and environment pollution problems require obtaining new solutions for a sustainable development [4].

Utilization of waste material and by-product is a partial solution to environment and ecological problems. Use of these materials helps in getting them utilized in cement, concrete and other constituent’s material. It also helps in reducing cost of cement and concrete manufacturing and also has numerous indirect benefits such as reduction in land filling cost, saving in energy and protecting the environment from possible pollution effects [34].

Further their utilization may improve the microstructure, mechanical and durability properties of mortar and concrete which are difficult to achieve by use of only ordinary Portland cement [3].

Waste materials are produced in high amounts and shapes ranging from large boulders to dust. Since large quantities of these wastes are generated daily, they are considered problematic and hazardous for both factories and the environment. Factories have to pay huge amount of money for the disposal of these materials, which in addition have a negative impact on environment [34].

The increased natural resource consumption has evolved into a major international problem with severe environment, social and financial consequences. Some industrial by-products show excellent properties as construction material, which means they could be used in concrete production not only for resource preservation but also to improve the mechanical properties and durability of final product [3].

1.2 ADVANTAGES OF USING INDUSTRIAL BY-PRODUCTS

Solid waste generation is mainly due to industrial and domestic activities. The waste generated due to industrial activities is of hazardous as well as non-hazardous nature. It is quite difficult to dump many industrial by-products such as fly ash and various kinds of slags [22].

Fly ash is one of the residues generated in combustion, and comprises the fine particles that rise with the flue gases. Ash which does not rise is termed bottom ash. In an industrial context, fly ash usually refers to ash produced during combustion of coal. Fly ash is generally captured by electrostatic precipitators or other particle filtration equipments before the flue gases reach the chimneys of coal-fired power plants, and together with bottom ash removed from the bottom of the furnace as is jointly known as coal ash. Depending upon the source and makeup of the coal being burned, the components of fly ash vary considerably, but all fly ashes include substantial amounts of silicon dioxide (SiO_2) (both amorphous and crystalline) and calcium oxide (CaO), both being endemic ingredients in many coal-bearing rock strata [9].

Since coal contains trace levels of arsenic, barium, beryllium, boron, cadmium, chromium, thallium, selenium, molybdenum and mercury, its ash will continue to contain these traces and therefore cannot be dumped or stored where rainwater can leach the metals and move them to aquifers. Where fly ash is stored in bulk, it is usually stored wet rather than dry so that fugitive dust is minimized. The resulting impoundments (ponds) are typically large and stable for long periods, but any breach of their dams or bunding will be rapid and on a massive scale [56].

Slag is a partially vitreous by-product of smelting the ore to separate the metal fraction from the unwanted fraction. It can usually be considered to be a mixture of metal oxides and silicon dioxide. However, slags can contain metal sulphides and metal atoms in the elemental form. While slags are generally used as a waste removal mechanism in metal smelting, they can also serve other purposes, such as assisting in the temperature control of the smelting; and also minimizing any re-oxidation of the final liquid metal product before the molten metal is removed from the furnace and used to make solid metal.

Large quantity of slag is produced by metal extracting industries. It is not easy to get rid of such a large volume of slag. Hence, it is many times used in making roads. Now a day it is commonly used in concrete making as it provides durability to structures. Slag cement is made by blending and inter-grinding OPC clinker and granulated slag in suitable proportions.

1.3 INDUSTRIAL BY-PRODUCTS IN INDIA

Huge quantities of by-products such as steel slag, silica fume, copper slag, phosphorus slag, ladle furnace slag etc. are generated from industries in India. The annual production from Bhilai steel plant (Durg, Chhattisgarh), Durga steel plant (Durgapur, West-Bengal), Tata steel plant (Jamshedpur, Jharkhand) and many other steel plants are shown in Table 1.3. Essar steel ltd (Hazira, India) produce Electric arc furnace slag, Ladle furnace slag is produced by industries such as Ghanpati Meta fluxes (Vishakhapatnam, Andhra Pradesh) and Cutwin Abrasive Industry (Jamnagar, Gujarat), KBN Industry (Tirunelveli, Tamil Nadu) produce copper slag and Maalu Ferro alloys PVT Ltd.(New Delhi, India) produce Ferrochromium slag in India.

1.4 SOURCES OF INDUSTRIAL BY-PRODUCTS

The following are the major source industries for by-products:

1. Metallurgical, steel making industries
2. Industrial and port/dock cleaning
3. Mechanical and automobile industries
4. Basic chemical industries
5. Oil refining and recycling industries

6. Power generation industries

1.5 DIFFERENT INDUSTRIAL BY-PRODUCTS

In the manufacturing of concrete the basic constituents such as cement can be replaced by material such as Granulated Blast furnace slag, Fly-ash, Silica fume, etc either as a binder, coarse aggregates by Electric arc furnace slag etc and fine aggregates by copper slag etc. The exact details of uses of these by-products are given in the Table 1.4.

In the present study by-products such as Silica fume, Steel making slag, Glass powder have been used to partially replace Cement as a Binder and Foundry sand, Copper slag and Phosphorus slag as a replacement of fine aggregates, Electric arc furnace slag and Ferrochromium slag as a replacement of coarse aggregates.

1.6 INDUSTRIAL BY-PRODUCTS FOR REPLACEMENT AS BINDERS

1.6.1 Ladle Furnace Slag

Ladle furnace basic slag, or refining slag, is produced in the final stages of steelmaking, when the steel is desulphured in the transport ladle, during what is generally known as the secondary metallurgy process. The liquid steel is at first subjected to an acid dephosphoration process in the BOF (oxygen blowing), after which it is poured into a ladle furnace where it is deoxidized, desulphured and suitably alloyed under the protection of a basic slag. More than 60% of its weight is made up of calcium and magnesium oxides; calcium oxide being indispensable for the basicity of the process, while the main role of the magnesium oxide is to protect the refractory walls of the ladle furnace. Silicon and aluminium oxides constitute the other main acid oxides of LFS, which jointly make up less than 40% of the total weight. The minor compounds in LFS are alkaline, iron, manganese and titanium oxides, sulphurs (from the steel desulphuration process), calcium fluoride and others that are even less significant [1-2]. The physical properties and chemical composition of ladle furnace slag are shown in Table 1.5.

1.6.2 Blast Furnace Slag

Blast furnace slag is a non-metallic material consisting essentially of silicates and aluminosilicates of calcium. The optimum content of these slags is as cementitious material components rather than as aggregates or for base stabilization. When the slag is allowed to cool slowly in the air, it solidifies into gray crystalline material known as crystallized slag. When the slag is cooled very rapidly by water, it solidifies and granulates as a granulated slag. Ground granulated blast furnace (GGBFS) has been used for many years as a supplementary cementitious material in Portland cement concrete, either as a mineral admixture or a component of blended cement [10].

GGBFS is a quite variable material due to the variability of its chemical composition. Offering latent hydraulic properties when mixed with clinker cement, hydration of slag is directly related to its hydraulicity: the dissolution of slag glass fraction is ensured by hydroxyl ions (OH^-) resulting from the hydrolysis of Portlandite $Ca(OH)_2$ produced by the hydration of clinker. The hydration products formed in the cement matrix are mainly additional hydrated calcium silicates and aluminates (CSH, CAH). The resulting hydrated cementitious matrix presents good chemical resistance and a more refined pores structure. Therefore the mechanical performance and durability of mortars and concretes are improved [10]. The chemical compositions of blast furnace slag are shown in Table 1.6.

1.6.3 Fly-Ash

Fly ash is the by-product of the combustion of pulverized coal and is collected by mechanical and electrostatic separators from the fuel gases of power plants where coal is used as a fuel. More than 88 million tonnes of fly ash are generated in India each year. Most of the fly ash is of Class F type. Class F fly ash obtained from thermal power plant at Bathinda. Concrete containing high volumes of Class F fly ash exhibited excellent mechanical properties, good durability with regard to repeated freezing and thawing, very low permeability to chloride ions and showed no adverse expansion when reactive aggregates were incorporated into concrete [16]. The chemical composition and physical properties of fly-ash are shown in Table 1.7 & Table 1.8 respectively.

1.6.4 Steel-Making Slag

Steel slag is a by-product of the conversion of iron to steel process. Because the chemical composition of steel slags is highly variable, the mineral composition of steel slag also varies. Olivine, merwinite, C_3S, C_2S, C_4AF, C_2F, RO phase (CaO-FeO-MnO-MgO solid solution) and free-CaO are common minerals in steel slag. The presence of C_3S, C_2S, C_4AF and C_2F endorses steel slag cementitious properties [32].

Steel slag is used as asphalt concrete aggregate in some countries. High free-CaO content in steel slag may cause volume expansion problems. A speciality steel slag cement, which is composed mainly of steel slag, blast furnace slag and Portland cement, has been commercially marketed in China for more than 20 years and uses approximately 40% of the total steel slag production. This type of cement has the advantages of lower energy cost, higher abrasion resistance, lower hydration heat evolution and higher later strength development, but the disadvantage of longer setting time and lower early strength when compared with Portland cement. Steel slag cement can be used for general construction use, especially suitable for mass concrete and pavement applications due to its special features. The mineralogical composition of steel slag changes with its chemical composition. Table 1.9 summaries the relationship between basicity, main mineral phase and reactivity of steel slag. It can be seen that the reactivity of steel slag increases with its basicity. However, free-CaO content also increases with the basicity of steel slag. The C_3S content in steel slag is much lower than in Portland cement. Thus, steel slag can be regarded as a weak Portland cement clinker [45]. The chemical compositions of steel slag are shown in Table 1.10.

1.6.5 Glass Powder

Glass in general is a highly transparent material formed by melting a mixture of materials such as silica, soda ash, and $CaCO_3$ at high temperatures followed by cooling during which solidification occurs without crystallization. Glass is widely used in our lives through manufactured products such as sheet glass, bottles, glassware, and vacuum tubing. We can use recycling waste glasses (crushed waste glasses such as amber, emerald green, flint, and mixed glass) as fine aggregates for concrete. WGP shows pozzolanic properties when it is grinded finer than 75 micro meters but when it is grounded finer than 45 micro meters then it ceases to behave as an ASR aggregate.ASR forms silicates and represents the durability of concrete.WGP can also be used as a fine aggregate when it is finer than 45 micro meter.PET polymer pellets are sometimes used in place of sand but it eventually results in lack of water absorption capacity of concrete thus reducing hydration [24]. Table shows the chemical and physical properties of waste glass. The chemical composition and physical properties of waste glass are shown in Table 1.11 & Table 1.12 respectively.

1.6.6 Silica Fume

Silica fume (SF), which is a by-product of the smelting process in the silicon and ferrosilicon industry. Silica fume (SF) is a by-product of the silicon and ferrosilicon industry. The reduction of high-purity quartz to silicon at temperatures up to 2000 °C produces SiO_2 vapours, which oxidizes and condense in the low-temperature zone to tiny particles consisting of non-crystalline silica. By-products of the production of silicon metal and the ferrosilicon alloys having silicon contents of 75% or more contain 85–95% non crystalline silica. The by-product of the production of ferrosilicon alloy having 50% silicon has much lower silica content and is less pozzolanic. Therefore, SiO_2 content of the silica fume is related to the type of alloy being produced [40]. Silica fume is a very reactive pozzolanic material because of its extreme fineness and very high amorphous silicon dioxide content. Silica fume concrete is stronger than silica fume cement paste.Silica-fume Concrete for use in rock stabilization, mine tunnel linings, and rehabilitation of deteriorating bridge and marine columns, piles high- way bridges, parking decks, marine structures and bridge deck overlays [46]. The chemical composition and physical properties of silica fume are shown in Table 1.13 & Table 1.14 respectively.

1.6.7 Metakaolin

Metakaolin is a cementitious material used as admixture to produce high strength concrete. It is an ultra-fine material produced by the dehydroxylation of a kaoline precursor upon heating in the temperature range of 700–800 and has high pozzolanic properties. MK is an ultra fine pozzolana, produced by calcining kaolin at temperatures between 700 and 900 C and consists predominantly of silica and alumina. Metakaolin is composed of non-crystalloidal SiO_2, similar to that of silica-fume, as well as crystalloidal SiO_2, mica components, and the presence of C–S–H and C–A–H constituting the main substances generated by the hydration [41-42]. The chemical composition and physical properties of metakaolin are shown in Table 1.15 & Table 1.16 respectively.

1.7 INDUSTRIAL BY-PRODUCTS FOR REPLACEMENT AS COARSE AGGREGATE

1.7.1 Electric Arc Furnace Slag

Electric arc furnace (EAF) slag, a by-product of steelmaking recovered after the oxidizing process, is useful when employed as aggregate in Concrete mixtures. Electric arc furnaces currently account for more than 40% of global steel production. Oxidizing slag taken from the EAF has to undergo the following conditioning process prior to its use as an aggregate [6]:

- Reduction to standard aggregate sizes following appropriate crushing.
- Stabilisation by exposure to weathering over several weeks.
- Appropriate crushing produces a maximum-sized aggregate of between 20 and 30 mm, and its grading presents a low proportion of fine fractions.

Electric arc furnace oxidizing slag, obtained from the manufacture of plain and low-alloy carbon steels, can be used as aggregate in concrete following appropriate conditioning. Special attention must be paid to the crushing process to produce a suitable grading. The chemical composition and physical properties of electric arc furnace are shown in Table 1.17 & Table 1.18 respectively.

1.7.2 Ferrochromium Slag

The high-carbon ferrochromium slag is waste material obtained in the manufacture of high-carbon ferrochromium, FeCr(C). The high-carbon FeCr metal with 65% Cr (min) content is produced in electro-arc furnaces by the carbo- thermal process out of the oxide of chromium ore (the chrome spinel with the Cr_2O_3-to-FeO ratio more than 2.5) with coke as the reducing agent at the temperature of about 1700^0C [38]. Both the liquids of the FeCr metal and of the slag flow out into ladles. After stratification of the metal from the slag by means of their different specific gravities, the molten slag, slowly cooling in the air, forms a stable crystalline dense rock product with mechanical properties similar to basalt. This slag has been used for a long time as road construction material [47]. The chemical composition and physical properties of ferrochromium are shown in Table 1.19 & Table 1.20 respectively.

1.8 INDUSTRIAL BY-PRODUCTS FOR REPLACEMENT AS FINE AGGREGATE

1.8.1 Copper Slag

Copper slag is a by-product during matte smelting and converting. The objective of matte smelting is to produce two separate liquid phases: copper-rich matte (sulphides) and slag (oxides). The oxides and sulphides combine into ore covalently Cu-Fe-O-S phase in the absence of silica. When silica is present, however, it combines with the oxides to form strongly bonded silicate anions:

$$2FeO+3SiO_2 \longrightarrow 2Fe^{2+} + Si_3O_8^{4-}$$

Which group together to form slag phase. The sulphides show no tendency to form these anion complexes and hence they remain as distinct covalent matte phase, quite dissimilar to the silicate slag. Silica is added directly for the most complete isolation of copper in matte occurs at near saturation concentration with SiO_2. Certain amount of lime and aluminium are added to stabilize the slag structure. The molten slag is discharged from the furnace at 1000 – 1300°C. If the molten slag is water-quenched, a glassy copper slag is obtained. Since copper slag usually has a low content of CaO, granulated copper slag exhibits pozzolanic properties. As CaO content in copper slag increases, it can exhibit cementitious properties [48]. The chemical composition and physical properties of copper slag are shown in Table 1.21 & Table 1.22 respectively.

1.8.2 Phosphorous Slag

Phosphorus Furnace Slag is by-product obtained in the extraction of phosphorus from rock-phosphate. Rock phosphate admixture with coke as a reducing agent and silica as a flux is melted in an electric arc furnace. Fluor-apatite, the major mineral in rock phosphate is reduced to elemental phosphorous and calcium silicate (slag) contaminated with calcium fluoride and other impurities are obtained as a by-product [49]. The process reactions can be presented as below:

When Fluor-apatite is involved in the reaction-

$$4Ca_5F(PO_4)_3 + 18SiO_2 + 30C \rightarrow 18CaO.SiO_2 \text{ (Slag)} + 2CaF_2 + 30CO + 3P_4$$

Phosphorus Furnace Slag

And when calcium phosphate is used in the reaction then reaction is as follow:

$$Ca_3(PO_4)_2 + 3SiO_2 + 5C \rightarrow 3CaSiO_3 \text{ (Slag)} + 2P + 5CO$$

Phosphorus Furnace Slag

Physical properties of Phosphorus Slag

Bond's Grind ability Index of Granulated Phosphorus furnace slag was found to be 14.0 Kwh/short tonne, which is lower than Bond's Grind ability Index for Indian blast furnace slags (15-18 Kwh/short tonne). A typical phosphorus furnace slag contains about 2 percent residue on 8 mm sieve and contains high residue on 500µ sieve (35.03 percent) [49]. The chemical compositions of phosphorus slag are shown in Table 1.23.

1.8.3 Foundry Sand

Foundry sand is high quality silica sand that is a by-product from the production of both ferrous and nonferrous metal castings. In the casting process, molding sands are recycled and reused multiple times. Eventually, however, the recycled sand degrades to the point that it can no longer be reused in the casting process. At that point, the old sand is displaced from the cycle as by-product. There are two basic types of foundry sand available, green sand (often referred to as molding sand) that uses clay as the binder material, and chemically bonded sand that uses polymers to bind the sand grains together [43]. The chemical compositions of chemical foundry sand and green foundry sand are shown in Table 1.24.

1.9 SCOPE OF PRESENT WORK

In the present work, various industrial by-products have been used as partially replacement of cement and sand. In today's construction scenario there is an acute shortage of fine aggregate (sand) and also cement production is highly energy intensive, costly and adversely affects the environment. The present study aims to reduce the quantity of cement and sand in concrete mixture by using different industrial by-products with improved compressive strength, tensile strength and durability of concrete. The study was completed using the design of experiment methodology to optimise various parameters that affects the compressive strength, splitting tensile strength and durability of concrete.

1.10 FORMATION OF THESIS

This thesis is divided in seven chapters as detailed below:

Chapter -1 This chapter provides an introduction to concrete, physical and chemical characteristics of various industrial by-products which can be used as a substitution of cement, coarse aggregate and fine aggregate and reasons and advantages of using industrial by-products.

Chapter -2 Literature review presents the workdone by various researchers in the field of using Industrial by-products in concrete.

Chapter-3 Details of optimum experimental design method (Taguchi method), parameters, objective functions and measuring equipment used, scheme of experiments, material used, variables involved, concrete mixes, mix design, casting, curing and testing of specimen and materials.

Chapter -4 This chapter provide results and discussion of various parameters studied using approach-1 standard statically analysis (ANOVA). Further optimization of parameters is shown.

Chapter -5 This chapter provide results and discussion of various parameters using approach-2 studied using standard statically analysis (ANOVA). Further optimization of parameters is shown.

Chapter -6 This chapter provide results and discussion of compressive strength for 7 days of curing time studied using standard statically analysis (ANOVA). Further optimization of parameters is shown.

Chapter -7 This chapter provide results and discussion of various parameters studied using standard statically analysis (ANOVA). It also provides the major conclusion made in the study and the future scope of work.

Chapter -8 References follow in succession.

Table 1.1 Chemical composition of the cement [43]

Composition	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO3	Na_2O	K_2O
%	20.19	5.25	3.68	62.81	1.8	3.02	0.15	0.86

Table 1.2 Physical properties of Cement (as per CEM 142.5 N) [3]

App. density(kg/m^3)	3140
Fineness(% retained at 45 μm)	11
Specific Surface (m^2/g)	0.962
Initial time setting (min)	125
Expansion(mm)	-
28-day pozzolanicity index (%)	100

Table 1.3 Plant-wise Average Generation of Steel slag 2006-07 and 2007-08 [44]

Steel Plant	**Production (In kg/ton of hot metal)**	
	2006-07	**2007-08**
Bhilai steel plant, Durg, Chhattisgarh	404	408
Visvesvaraya Iron & steel plant, Bhadravati, Karnataka	320	318
Durga steel plant, Durgapur, West-Bengal	362	365
Tata steel plant, Jamshedpur, Jharkhand	239	247
IISCO steel plant, Burnpur, West-Bengal	509	582
IDCOL kalinga iron works Ltd, Barbil, Orissa	380	380
JSW steel Ltd, Bellary, Karnataka	348	412

Table 1.4 Different Industrial By-Products

Basic Concrete Materials	Proposed Replacements
Cement(Binder)	1. Silica Fume 2. Fly Ash 3. Granulated Blast Furnace Slag 4. Metakaolin 5. Glass Powder with lithium nitrate 6. Steel making slag 7. Municipal Solid Waste Incinerator(MSWI) ash mix slag 8. Rice Husk Ash 9. Ladle Furnace Slag 10. Copper Slag 11. Cement kin dust 12. Wood Ash 13. Foundry Bag House Dust
Fine Aggregates (sand)	1. Chemical Foundry Sand 2. Green Foundry Sand 3. Poly-Ethylene Terephthalate(PET) 4. Fine Glass Powder 5. Crushed Granite 6. Fly Ash 7. Quarry Dust 8. Crumb Rubber 9. Copper Slag 10. Phosphorus Slag 11. Bottom Ash 12. Boiler Slag

Coarse Aggregates	1. Cooled Blast Furnace Slag 2. Ferrochromium Slag 3. Crushed Hydraulic Cement Concrete 4. Electric Arc Furnace Slag 5. Cupola Furnace Slag

Table 1.5 Physical properties and chemical composition of Ladle furnace slag [2]

Apparent density	2.83 Mg/m^3
Specific surface - Blaine value	266-390 m^2/kg
CaO	56%
SiO_2	17%
Al_2O_3	11%
MgO	10%
Fe_2O_3	2%
∑ others ($Mno+TiO_2+SO_3+Na_2O+K_2O$)	4%
Free lime [$CaO+Ca(OH)_2$]	12%
Free MgO (periclase)	6%
LOI	5%

Table 1.6 Chemical composition of Blast furnace slag [10, 13]

Chemical Composition	**Slag (%)**
Fe_2O_3	2.11
SiO_2	40.30
CaO	40.12
Al_2O_3	8.12
∑ others ($Na_2O + K_2O + SO_3$)	1.9
MgO	4.23
Loss on Ignition	1.96

Table 1.7 Chemical composition of Fly-ash (Class F) [16]

Chemical composition	Slag (%)
Fe_2O_3	5.40
SiO_2	57.3
CaO	6.10
Al_2O_3	27.1
∑ others ($Na_2O + K_2O + SO_3$)	2.40
TiO_2	1.30
Loss on Ignition	0.50
MgO	2.00
Moisture	0.50

Table 1.8 Physical properties of Fly-ash (Class F) [17]

Specific gravity	Fineness	Bulk density	Blaine Fineness	Pozzolanic activity index
2.20	3150	995 kg/m^3	310 m^3/kg	75

Table 1.9 Reactivity, basicity and mineral compositions of steel slags [32]

Reactivity	Types of steel slag	Basicity		Main mineral phase
		CaO/SiO_2	$CaO/ (SiO_2 + P_2O_5)$	
Low	Olivine	0.9–1.5	0.9–1.4	Olivine, RO phase and merwinite
Medium	Merwinite dicalcium silicate	1.5–2.7	1.4–1.6 1.6–2.4	Merwinite, C2S and RO phase C2S and RO phase
High	Tricalcium silicate	>2.7	>2.4	C3S, C2S, C4AF, C2F and RO phase

Table 1.10 Chemical composition of steel slag [45]

Chemical composition	Steel slag (%)
Fe_2O_3	23.86
SiO_2	17.09
CaO	40.46
Al_2O_3	4.53
∑ others (Na_2O+ SO_3+ TiO_2)	1.42
MgO	10.46
Loss on Ignition	0.91

Table 1.11 Chemical composition of waste glass [24]

Type	Chemical composition		
	Emerald green glass (%)	Amber glass (%)	Flint glass (%)
SiO_2	71.30	72.10	73.04
Al_2SO_3	2.18	1.74	1.81
Na_2O+ K_2O	13.07	14.11	13.94
CaO+ MgO	12.18	11.52	10.75
SO_3	0.053	0.13	0.22
Fe_2O_3	0.596	0.31	0.04
Cr_2O_3	0.44	0.01	-----
Grain shape	Angular	Angular	Angular

Table 1.12 Physical properties of waste glass [24]

Type	FM	Specific gravity	Water absorption (%)	Absolute volume (%)	Unit weight (kg/m^3)
Amber	3.49	2.52	0.40	61.93	1559
Emerald green	3.48	2.50	0.41	61.78	1543
Flint	3.48	2.50	0.43	62.60	1551

Table 1.13 Chemical compositions of Silica fume (%) [40]

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2	P_2O_5	MnO
92.0	0.48	2.11	0.40	0.63	0.87	0.28	1.24	<0.01	0.02	0.23

Table 1.14 Physical properties of Silica fume [46]

Specific gravity	Surface area (cm^2/g)	Bulk density (densified)	Insoluble residue (%)	Loss of Ignition	Particle size (Typical)
2.2	13,000-30,000	480-720 kg/m^3	-------	2.54	< 1μm

Table 1.15 Chemical composition of Metakaolin [42]

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	TiO_2
52.1%	41.0%	4.32%	0.07%	0.19%	------	0.26%	0.63%	0.20%

Table 1.16 Physical properties of Metakaolin [41-42]

Specific gravity	Surface area (cm^2/g)	Appearance	Insoluble residue (%)	Loss of Ignition	Free Lime (%)	Bulk density
2.63	120000	Light pink	-------	0.60	-------	0.4 - 0.5

Table 1.17 Chemical composition of Electric arc furnace slag [6]

Chemical composition	**EAF slag**
∑Iron oxides	42.5
SiO_2	15.3
CaO	23.9
Al_2O_3	7.4
MgO + MnO	9.6
∑ Others(P_2O_5+TiO_2+Na_2O+K_2O+ SO_3)	1.1

Table 1.18 Physical properties of Electric arc furnace slag [6]

Property	Coarse slag	Fine slag
Size (mm)	4-20	0-4
Proportion after primary crushing %	76	24
Apparent specific gravity (Mg/m^3)	3.35	3.70
Water absorption (%)	10.5	-----
Loss angles loss (%)	<20	-----
Expansion average (ASTM D-4792)	0.25 %	0.25 %

Table 1.19 Chemical composition of Ferrochromium slag [38]

Chemical composition, mass %	**Original FeCr slag**	**Slag after "jig treatment"**
Cr_2O_3/Cr	13.50/9.24	5.20/3.55
FeO/Fe	2.60/2.02	1.00/0.78
SiO_2	33.40	34.00
Al_2O_3	15.40	16.30
MgO	33.23	41.80
CaO	2.10	1.60
Sulphur as SO_3	0.45	0.50
chloride	------	------

Table 1.20 Physical properties of Ferrochromium slag [47]

Property	**Ferrochromium slag**
Bulk density	1.88
Apparent specific gravity (Mg/m^3)	3.15
Water absorption (%)	2.32
Loss angles abrasion value (%)	18.58
Freeze thaw resistance (%)	4.12

Table 1.21 Physical properties of Copper slag [48]

Physical Properties	**Copper slag**
Particle shape	Irregular
Appearance	Black & glassy
Type	Air cooled
Specific gravity	3.91
Percentage of voids	43.20%
Bulk density	2.08 g/cc
Fineness modulus of copper slag	3.47
Angle of internal friction	$51^{o}20'$
Hardness	6-7 mohs
Water absorption	0.3 to 0.4%
Moisture content	0.1%
Fineness of copper slag	125 m^2/kg

Table 1.22 Chemical composition of Copper slag [48]

Chemical composition	**Copper slag (%)**
Fe_2O_3	68.29
SiO_2	25.84
CaO	0.15
Al_2O_3	0.22
$\sum$ others ($Na_2O + K_2O + SO_3$)	0.92
LOI	6.59
TiO_2	0.41
CuO	1.20
Mn_2O_3	0.22
Sulphide Sulphur	0.25
Insoluble residue	14.88

Table 1.23 Chemical composition of phosphorous slag [49]

Chemical composition	Super fine Phosphorous slag (%)
Fe_2O_3	2.93
SiO_2	36.88
CaO	44.40
Al_2O_3	3.92
P_2O_5	0.60
MgO	1.56
Na_2O	0.58
SO_3	0.18
Loss on Ignition	2.80

Table 1.24 Primary composition of chemical foundry sand (QFS), green foundry Sand (GFS) [43]

Chemical composition	Chemical foundry sand	Green foundry sand
Fe_2O_3	0.49	3.32
SiO_2	95.10	84.90
CaO	0.19	0.58
Al_2O_3	1.47	5.21
P_2O_5	0.02	0.05
MgO	0.19	0.67
LOI	1.32	2.87
Na_2O	0.26	0.50
TiO_2	0.04	0.19
K_2O	0.68	0.97
Cr_2O_3	0.21	0.37
SO_3	0.03	0.29

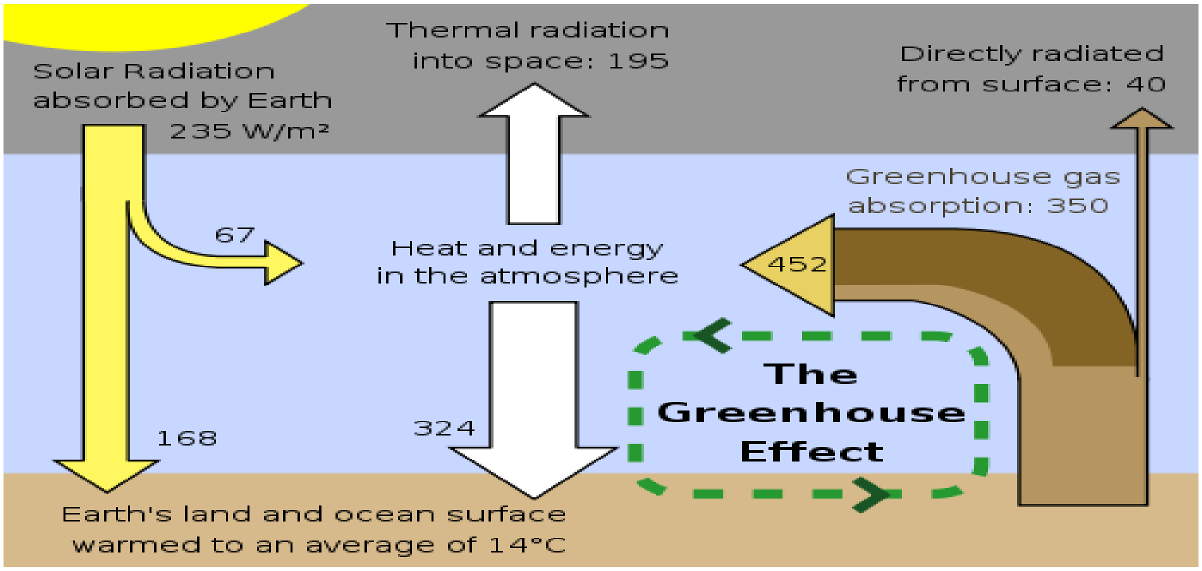


Figure 1.1 Green house effect [52]

2.0 GENERAL

A lot of research work was carried out throughout the world for predicting the strength and durability of concrete using industrial by-products and waste. A brief review of literature is being presented here:

2.1 LADLE FURNACE SLAG

Adolfsson *et al.* [1]

The present study was aimed at investigating the hydraulic characteristics of ladle furnace slag (LFS), under the pretence of using LFS as a cement substitute in certain applications. Mortar prisms of LFS exhibited good performance by measuring 33.1 MPa after 2 days and 34.9 MPa after 7 days. The strength development agrees with the formation of C_2AH_8 and C_4AH_{19}, which were found after 24 h in samples analyzed with calorimetry. From 7 days up to 28 days hydration, the compressive strength dropped 13 MPa down to 21.9 MPa, which suggests a conversion to the thermodynamically stable C_3AH_6. The result also suggests that Q-phase at this stage of the hydration has not started to form stratlingite, to any significant extent (which is reported as a hydration product of Q-phase) since the formation of C_2ASH_8 would have prevented the decline in strength. The argument also seemed to hold true with regard to the amorphous phase that accounts for about 35 wt. % of the material. The blend with GGBFS reacted more slowly than neat LFS as could be expected. The strength was determined to 17.9 MPa after 2 days and 16.4 MPa after 7 days. The strength after 28 days however, was superior to LFS by measuring 31.6 MPa. The increase in strength reflects the formation of C_2ASH_8 which is explained by an activation of the GGBFS that was apparent already after 24 h at the same temperature (20 °C) when we are using 50% LFS, and 50% ground granulated blast furnace slag (GGBFS).

Manso et *al.* [2]

This study examined the properties of masonry mortars made with ladle furnace basic slag and the other conventional components such as sand, cement, and admixtures.

Eight different mixes were prepared and the main properties of the resulting mortars were analyzed: density, strength, porosity, microstructure and permeability. The porosity of the hardened mixes was studied by means of two complementary techniques: mercury intrusion porosimetry and computerised X-ray tomography. Finally, tests were performed to analyze the behaviour of the mixes exposed to standard detrimental agents such as frost, moisture and sulphates, as well as other special environments, such as saline water or sulphidic atmospheres. The results show that the presence of ladle furnace slag does not damage and even contributes to increasing mortar durability. Its use also decreases or eliminates volumetric contraction during mortar ageing, thereby improving certain masonry applications.

Papayianni et *al.* [3]

The production of a high-strength, high performance concrete using high volumes of industrial by-products was tested in laboratory mixtures. The by-products used were high-calcium fly ash and ladle furnace slag as binders and electric arc furnace slag as aggregates. Fly ash was used as 50% by mass of the total binder and ladle furnace slag as 30% by mass of the total binder. Slag aggregates were used in replacement of coarse aggregate or in replacement of both fine and coarse aggregates. In the mixtures containing both supplementary cementitious materials and slag aggregates the produced concrete shows high-strength (>70 MPa), good abrasion resistance and fracture toughness.

Rodriguez et *al.* [4]

This paper discussed the attractive option of using LFS in the manufacture of masonry mortars for use in the construction industry, which required an analysis of the principal characteristics of such mortars, i.e. workability and mechanical strength. It reported a comparative study, using standard commercial admixtures, between conventional masonry mortars and mortars manufactured with LFS as a partial replacement for sand and cement, the results of which imply considerable economic savings in sand and cement, improvements in the properties of the mortars and in overall sustainability, by avoiding disposal and conserving natural resources.The incorporation of LFS to complement sand and in partial replacement of cement reduced, and in some cases completely avoids the need to use admixtures in masonry mortars. Furthermore, considering mixtures with similar levels of Portland cement consumption, the incorporation of LFS improves the volumetric efficiency of the fresh mortar by approximately 40% due to the LFS added volume, and the volume of a short addition (7% weight) of siliceous sand.

Setien et *al.* [5]

This paper presented the data characterizations of several kinds of LFS, setting out referential values for their use in construction and civil engineering applications that referred to chemical, mineralogical and micro structural data as well as to thermal and infrared analytical results. The aim was to provide a detailed overview of this material for anyone with an interest in gaining further knowledge of its specific properties for application as a construction material. The potential hydration and carbonation reactions of LFS can involve volumetric changes, strength gain and conversion, which means that the inclusion of this material in rigid (mortar or concrete) or flexible (soils or embankments) matrices is an important decision that should be given careful consideration.

2.2 ELECTRIC ARC FURNACE SLAG

Juan M. Manso *et al.* [6]

This paper detailed a systematic study of slag concrete behaviour under severe test conditions. The tests were designed to evaluate the internal expansivity of the slag, its chemical reactivity with some components of the cement and its resistance to environmental agents, ice and moisture. The results indicated that the durability of slag concrete is acceptable, though slightly lower than that of conventional concrete. When the mix proportions were adequate, both the mechanical strength and the durability of slag concrete are satisfactory, although in less care mixes durability is likely to be impaired. Electric arc furnace (EAF) slag, a by-product of steelmaking recovered after the oxidizing process, was useful when employed as aggregate in hydraulic concrete and bituminous mixtures. Concrete made with EAF oxidizing slag as an aggregate shows good physical and mechanical properties and further study of its durability will ensure greater reliability in its usage.

Pellegrino *et al.* [7]

The study was undertaken to investigate the opportunity to largely substitute natural aggregates of traditional concrete with Black/Oxidizing Electric Arc Furnace (EAF) slag. Compressive and tensile strength, elastic modulus and durability characteristics (accelerated aging, freezing and thawing, wetting and drying) of concrete containing EAF slag as aggregate according to Fuller's ideal grading curve were experimentally investigated. This study aimed to improve the scarce database of mechanical and durability tests on this type of concrete and gave some insights to improve durability properties of concrete made with EAF slag, not only using modern agents and additives, but also working on the actual grading curve of aggregates used, closely connected to the overall durability for any kind of concrete. Concrete made with EAF slag as aggregate showed good strength characteristics since, in normal environmental conditions, strength properties of the conglomerate containing EAF slag were totally comparable (or even better) than those observed for traditional concrete. Conversely, the typical chemical and physical properties of EAF slag, such as the high content in calcium and magnesium oxides inclined to hydration, may be a limit for the durability of the resulting concrete: on one hand the durability can be strongly improved even in critical freezing/thawing environmental conditions by a small amount of air-entraining agent, on the other hand, this conglomerate still remains rather vulnerable to repeated cycles of wetting and drying.

Muhmood et *al.* [8]

The cementitious and pozzolanic behavior of electric arc furnace steel slag, both as received and treated was studied in detail. This received slag was completely crystalline and multiphasic with Fe-substituted monticellite as the predominant phase. Treatment of that slag, remelting and water quenching, results in reduction of Fe-oxide content coupled with an increase in basicity index which makes it more hydraulic compared to the as received slag. The remelted slag has several phases with merwinite as the dominant phase. Thermal analysis of the hydrated slag showed that treating them as received slag increases the water absorption capacity, a property essential for cementitious behavior. Compression strength of the slag blended cements was studied and it was found that substitution of 20% ground granulated blast furnace slag with electric arc furnace steel slag does not decrease the strength beyond 28 days. The control cement has a strength of 58.6 MPa compared to 58 MPa for the cement comprising of 20% untreated slag. The substitution of that untreated slag with treated slag exhibited the highest strength, 61 MPa and a potential for further strength increase after 28 days. In the case of cement mix with no blast furnace slag, substitution of 15% clinker with steel slag did not decrease the strength significantly, 64.4 MPa compared to 66.5 MPa for the control cement. Substituting 30% clinker in the cement mix with electric arc furnace slag however results in significant decrease in strength, 53.4 MPa. The pozzolanic strength of the slag was found to increase significantly due to remelting from 2.0 MPa for the as received slag to 8.0 MPa for the treated slag.

Maslehuddin et *al.* [9]

This paper presented the results of a study conducted to evaluate the mechanical properties and durability characteristics of ordinary Portland cement (OPC) and blended cement (silica fume and fly ash) concrete specimens prepared with electric arc furnace dust (EAFD). Concrete specimens were prepared with and without EAFD. In the silica fume cement concrete, silica fume constituted 8% of the total cementitious material while fly ash cement concrete contained 30% fly ash. EAFD was added as 2% replacement of cement in the OPC concrete and 2% replacement of the total cementitious content in the blended cement concretes. Mechanical properties, such as compressive strength, drying shrinkage, initial and final setting time, and slump retention were determined. The durability characteristics were evaluated by measuring water absorption, chloride permeability, and reinforcement corrosion. The initial and final setting time and slump retention increased due to the incorporation of EAFD in both OPC and blended cement concretes. The drying shrinkage of EAFD cement concrete specimens was more than that of concrete specimens without EAFD. The incorporation of EAFD was beneficial to OPC concrete in terms of strength gain while such a gain was not noted in the blended cement concretes. However, the strength differential between the blended cement concretes with EAFD and the corresponding concretes without EAFD was not that significant. The water absorption and chloride permeability, however, decreased due to the incorporation of EAFD in both the OPC and blended cement concretes. The corrosion resistance of OPC and blended cement concrete specimens increased due to the addition of EAFD.

2.3 BLAST FURNACE SLAG

Nazari & Riahi [10]

In this work, strength assessments and percentage of water absorption of self compacting concrete containing different amounts of ground granulated blast furnace slag and TiO_2 nanoparticles as binder were investigated. Portland cement was replaced by 45 wt% of ground granulated blast furnace slag and up to 4.0 wt% TiO_2 nanoparticles and the properties of concrete specimens were investigated. TiO_2 nanoparticles as a partial replacement of cement up to 3.0 wt% could accelerate C–S–H gel formation as a result of increased crystalline Ca $(OH)_2$ amount at the early age of hydration and hence increase strength and improve the resistance to water permeability of concrete specimens. Several empirical relationships were presented to predict flexural and split tensile strength of the specimens by means of the corresponding compressive strength at a certain age of curing.

Nazari & Riahi [11]

In the present study, split tensile strength together with pore structure, thermal behavior and microstructure of concrete containing ground granulated blast furnace slag and SiO_2 nanoparticles were investigated. Portland cement was replaced by different amounts of ground granulated blast furnace slag and the properties of concrete specimens were measured. Although it negatively impacts the properties of concrete at early ages, ground granulated blast furnace slag was found to improve the physical and mechanical properties of concrete up to 45 wt% at later ages. SiO_2 nanoparticles with the average particle size of 15 nm were partially added to concrete with the optimum content of ground granulated blast furnace slag and physical and mechanical properties of the specimens were studied. SiO_2 nanoparticles as a partial replacement of cement up to 3 wt% could accelerate C–S–H gel formation as a result of increased crystalline Ca $(OH)_2$ amount at the early age of hydration and hence increase split tensile strength of concrete specimens. The increased the SiO_2 nanoparticles' content more than 3 wt% causes the reduced the split tensile strength because of the decreased crystalline $Ca(OH)_2$ content required for C–S–H gel formation.

Vejmelkova et *al.* [12]

Rheological, mechanical and durability properties of self-compacting concrete (SCC) mixes produced using blended binders containing metakaolin and blast furnace slag were studied. The compressive strength of SCC with metakaolin grows very fast during the initial hardening period and remains significantly higher, as compared with the mix with blast furnace slag, up to 90 days. Durability properties of the mix containing metakaolin are excellent. Water absorption coefficient and water penetration depths were very low. The freeze resistance tests show zero mass loss after 56 cycles in deicing salt solution.

Siddique & Kaur [13]

This paper deals with the mechanical properties of concrete made with ground granulated blast furnace slag (GGBFS) subjected to temperatures up to 350^0C. For this purpose, normal concrete having compressive strength of 34 MPa was designed using GGBFS as partial replacement of cement. Cylindrical specimens were made and subjected to temperatures of 100, 200 and 350^0C. Measurements were taken for mass loss, compressive strength, splitting tensile strength, and modulus of elasticity. This investigation developed some important data on the properties of concrete exposed to elevated temperatures up to 350^0C.

Sadok [14]

In this paper, a Granulated Blast Furnace Slag with a low reactivity index was used in modifying mortar composition. Microstructure and durability of mixes containing 0%, 30% and 50% of slag as substitution to OPC were respectively compared and analyzed. The durability of mortar was evaluated through capillary water absorption and chloride diffusion tests. The results indicated finer porosity and lower water absorption for slag mortars at old ages (90 and 360 days). Moreover, lower chloride diffusion for 50% blast furnace slag substitution was observed.

Haha et *al.* [15]

The hydration and the microstructure of three alkali activated slags (AAS) with MgO contents between 8 and 13 wt. % were investigated. The slags were hydrated in the presence of two different alkaline activators, NaOH and $Na_2SiO_3 \cdot 5H_2O$ (WG). Higher MgO content of the slag resulted in a faster reaction and higher compressive strengths during the first days. The formation of C(− A)–S–H and of a hydrotalcite-like phase was observed in all samples by X-ray diffraction (XRD), thermal analysis (TGA) and scanning electron microscopy (SEM) techniques. Increasing the MgO content of the slag from 8 to 13% increased the amount of hydrotalcite and lowered the Al uptake by C–S–H resulting in 9% higher volume of the hydrates and a 50 to 80% increase of the compressive strength after 28 days and longer for WG activated slag pastes. For NaOH activated slags only a slight increase of the compressive strength was measured.

2.4 FLY-ASH

Siddique [16]

This article presented the results of an experimental investigation dealing with concrete incorporating high volumes of Class F fly ash. Portland cement was replaced with three percentages (40%, 45%, and 50%) of Class F fly ash. Tests were performed for fresh concrete properties: slump, air content, unit weight, and temperature. Compressive, splitting tensile and flexural strengths, modulus of elasticity, and abrasion resistance were determined up to 365 days of testing. Test results indicated that the use of high volumes of Class F fly ash as a partial replacement of cement in concrete decreased its 28-day compressive, splitting tensile and flexural strengths, modulus of elasticity, and abrasion resistance of the concrete. However, all these strength properties and abrasion resistance showed continuous and significant improvement at the ages of 91 and 365 days, which was most probably due to the pozzolanic reaction of fly ash. Based on the test results, it was concluded that Class F fly ash can be suitably used up to 50% level of cement replacement in concrete for use in precast elements and reinforced cement concrete construction.

Jo et *al.* [17]

An experiment was performed to investigate the properties of the hardened paste of fly ash by alkali activation and to determine the possible use of the paste in the production of lightweight aggregates. The highest compressive strength was 33.9 MPa, for paste with 10% NaOH, 15% sodium silicate, and 5% MnO_2, cured at room temperature after 24 h of moisture curing at 50^0C. The hardened paste of fly-ash was granulated to produce AFLA (alkali-activated fly ash lightweight aggregate). AFLA exhibited specific gravity (SSD, OD), water absorption, unit weight, and solid volume percentages of 1.85 (SSD), 1.66 (OD), 11.8%, 972 kg/m3, and 58.6%, respectively. The results of the heavy metals leaching test met US EPA regulations. The concrete using AFLA exhibited a compressive strength of 26.47 MPa and good freeze–thaw resistance at 6.0% entrained air content.

Jiang et *al.* [18]

The carbonation, corrosion of steel reinforcement in concrete and corrosion resistance of concrete, incorporating large volumes of low- quality fly ash (LVLQFA), was studied. The effect of concentration of carbon dioxide used in the experiment on estimating the carbonation resistances of LVLQFA concrete were also investigated. Test results showed that the LVLQFA concrete with an activator has good carbonation and corrosion resistances of steel reinforcement. The corrosion resistance of LVLQFA concrete is better than that of the control concrete. The concentration of carbon dioxide used in the experiment has considerable effect on estimating the carbonation resistance of LVLQFA concrete. The use of an activator can improve the carbonation resistance of LVLQFA concrete. The carbonation resistance of LVLQFA concrete with an activator is close to the control concrete.

Atis [19]

A laboratory investigation was carried out to evaluate the strength properties of high-volume fly ash (HVFA) roller compacted and superplasticised workable concrete cured at moist and dry curing conditions. Concrete mixtures made with 0%, 50% and 70% replacement of normal Portland cement (NPC) with two different low-lime Class F fly ashes, good and low quality, were prepared. Water–cementitious material ratios ranged from 0.28 to 0.43. The compressive, flexural tensile and cylinder splitting tensile strengths were measured and presented. The relationship between the flexural tensile and compressive strengths was discussed. The influence of loss on ignition (LOI) content of fly ash on water demand and the strength of concrete was also discussed. The influence of moist and dry curing conditions on the high-volume fly ash (HVFA) concrete system was assessed through a proposed simple efficiency factor. The study showed that producing high-strength concrete was possible with high-volume fly ash content. LOI content increased the water demand of fresh concrete. HVFA concrete was found to be more vulnerable to dry curing conditions than was NPC concrete. It was concluded that HVFA concrete was an adequate material for both structural and pavement applications.

Sahmaran et *al.* [20]

This paper presented the transport and mechanical properties of self consolidating concrete that contain high percentages of low-lime and high-lime fly ash (FA). Self consolidating concretes (SCC) containing five different contents of high-lime FA and low-lime FA as a replacement of cement (30, 40, 50, 60 and 70 by weight of total cementitious material) were examined. For comparison, a control SCC mixture without any FA was also produced. The fresh properties of the SCCs were observed through, slump flow time and diameter, V-funnel flow time, L-box height ratio, and segregation ratio. The hardened properties included the compressive strength, split tensile strength, drying shrinkage and transport properties (absorption, sorptivity and rapid chloride permeability tests) up to 365 days. Test results confirmed that it is possible to produce SCC with a 70% of cement replacement by both types of FA. The use of high volumes of FA in SCC not only improved the workability and transport properties but also made it possible to produce concretes between 33 and 40 MPa compressive strength at 28 days, which exceeds the nominal compressive strength for normal concrete (30 MPa).

Nochaiya *et al.* [21]

This paper reported the normal consistency, setting time, workability and compressive strength results of Portland cement–fly ash–silica fume systems. The results showed that water requirement for normal consistency was found to increase with increasing SF content while a decrease in initial setting time was found. Workability, measured in term of slump, was found to decrease with silica fume content (compared to blends without silica fume). However, it must be noted that despite the reduction in the slump values, the workability of Portland cement–fly ash–silica fume concrete in most cases remained higher than that of the Portland cement control concrete. Furthermore, the utilization of silica fume with fly ash was found to increase the compressive strength of concrete at early ages (pre 28 days) up to 145% with the highest strength obtained when silica fume was used at 10 wt%. Moreover, scanning electron micrographs show that utilization of fly ash with silica fume resulted in a much denser microstructure, thereby leading to an increase in compressive strength.

Zhen-shuang [22]

Fly ash dumped not only consumes landfills, but also pollutes environment. With the aim of sustainable development, the isolated contribution of fly ash in concrete to the mechanical properties of frame concrete was investigated, and experiments were carried out over water–binder ratios ranging from 0.30 to 0.42 and fly ash–binder ratios from 0% to 30%, based on concrete framework model theory. The compressive and flexural strengths of frame concrete and corresponding mortar matrix were determined on 28 days, 56 days and 90 days. The 28-day compressive and flexural strengths of concrete and mortar matrix decreased with fly ash incorporation, and increased on 56 days and 90 days due to curing ages and pozzolanic reaction. It can be concluded that the optimum of fly ash is not a constant one but depends on the water–cementitious materials (w/cm) ratio of the mix. Based on the test results, concrete framework equation was developed using statistical methods.

2.5 GLASS POWDER

Chidiac *et al.* [23]

This paper studied the use of glass powder in high strength concrete. It was shown that concrete shows pozzolanic properties when it was grinded finer than 75 micro meters but when it was grounded finer than 45 micro meters then it ceases to behave as an ASR aggregate.ASR formed silicates and represents the durability of concrete.WGP can also be used as a fine aggregate when it was finer than 45 micro meter.PET polymer pellets were sometimes used in place of sand but it eventually results in lack of water absorption capacity of concrete thus reducing hydration. However using these aggregates in optimized amounts result in concrete which is more stable and is less deviated from its initial strength. Waste glass powder (WGP) as a SCM because of its high silica content. Glass, which is an amorphous material, was shown to exhibit pozzolanic properties when ground finer than 75μm. WGP was used as cement replacement and, HDPE and LDPE polymer pellets were used as sand replacement. Use of up to 30% WGP as cement replacement yielded minor reduction in compressive strength when compared to the control at 28-days and comparable strength to the control at 90-days. A recent study has shown that WGP at up to 10%

cement replacement in concrete yields similar results to fly ash at the same replacement level after 90-days.

Park *et al.* [24]

This study was conducted through basic experimental research in order to analyze the possibilities of recycling waste glasses (crushed waste glasses such as amber, emerald green, flint, and mixed glass) as fine aggregates for concrete. Test results of fresh concrete show that both slump and compacting factors are decreased due to angular grain shape and that air content is increased due to the involvement of numerous small-sized particles that were found in waste glasses. In addition the compressive, tensile and flexural strengths of concrete were shown to decrease when the content of waste glass is increased. In conclusion, the results of this study indicate that emerald green waste glass when used below 30% in mixing concrete is practical along with usage of 10% SBR latex. In addition, the content of waste glasses below 30% is practical along with usage of a pertinent admixture that was necessary to obtain workability and air content.

Taha *et al.* [25]

This investigation studied the influence of two different mineral admixtures, lithium nitrate (Li) and pozzolanic glass powder (PGP) on the expansion induced by alkali-silica reaction (ASR).Test results confirmed that Li and PGP have significantly reduced the ASR expansion. Lower calcium to silica ratio (Ca/Si) was found in concrete mix contains (PGP) because of the high amorphous reactive silica and low calcium content in PGP compared to ordinary Portland cement CEM1. Alkali-silica reaction (ASR) is a deleterious reaction occurring between reactive siliceous minerals present in some aggregate and the alkaline pore solution in concrete. The use of pozzolanic glass powder is newly introduced as a novel method to mitigate ASR expansion. The amorphous structure of the glass promotes it to undergo pozzolanic reaction with the presence of alkaline activator, such as: lime, cement and alkalis (sodium and potassium) and contribute to the C–S–H structure and hydration products.

1. The ASR starts when the high alkaline pore solution of the Portlandite attacks the siliceous minerals in the reactive and unstable aggregate. The product of this chemical reaction is known as the alkali-silica gel which capable of absorbing

water and swell with a consequent tendency to increase in volume and generate internal pressure.

2. **Minimising ASR by low calcium ashes**: The alkali-silicate gel formation takes place only in the presence of enough amounts of Calcium ions (Ca++) in concrete. Therefore, even in concrete with very high alkali (Na_2Oeq) content, if the cement or any other cementing binder that used in the concrete has low calcium content, the ASR expansion was mitigated. Low calcium content such as GGBS, PFA and Metakaolin to replace the cement in the concrete.
3. **Minimising ASR by lithium compounds**: Lithium is recognized as a soft, silver-white and lightest dense metal and has an atomic number of three, with a density about half that of water (0.53 g/cm^3). It is a very reactive metal, because of its tendency to expel its outer electron. Lithium (Li) is classified as an alkali metal. A high lithium dosage was necessary to get sufficient amount of the lithium that taken up by the ASR gel. Therefore, it can overcome the concomitant increase in the OH ion challenge the presence of lithium in the structure of the ASR gel will reduce the tendency of the ASR gel to absorb water and swell.

Shi and Zheng [26]

The use of recycled waste glasses in Portland cement and concrete has attracted a lot of interest worldwide due to the increased disposal costs and environmental concerns. Being amorphous and containing relatively large quantities of silicon and calcium, glass is, in theory, pozzolanic or even cementitious in nature when it is finely ground. Thus, it can be used as a cement replacement in Portland cement concrete. The use of crushed glasses as aggregates for Portland cement concrete does have some negative effect on properties of the concrete; however, practical applicability can still be produced even using 100% crushed glass as aggregates. The main concerned for the use of crushed glasses as aggregates for Portland cement concrete was the expansion and cracking caused by the glass aggregates. This paper summarized the progresses and points out the directions for the proper uses of waste glasses in Portland cement and concrete.

Shayan *et al.* [27]

A large proportion of the postconsumer glass was recycled into the packaging stream again, and some smaller proportions were used for a variety of purposes, including concrete aggregate. However, a significant proportion, which did not meet the strict criteria for packaging glass, was sent to landfill, taking the space that could be allocated to more urgent uses. Glass was unstable in the alkaline environment of concrete and could cause deleterious alkali-silica reaction (ASR) problems. This property was used to advantage by grinding it into a fine glass powder (GLP) for incorporation into concrete as a pozzolanic material. In laboratory experiments, it can suppress the alkali reactivity of coarser glass particles as well as that of natural reactive aggregates. It undergoes beneficial pozzolanic reactions in the concrete and could replace up to 30% of cement in some concrete mixed with satisfactory strength development. The drying shrinkage of the concrete containing GLP was acceptable. It was concluded that 30% GLP could be incorporated as cement or aggregate replacement in concrete without any long-term detrimental effects. Up to 50% of both fine and coarse aggregates could also be replaced in concrete of 32-MPa strength grade with acceptable strength development properties.

Shayan et *al.* [28]

In order to investigate the performance of GLP in concrete under field conditions, a field trial was conducted using a 40 MPa concrete mixture, incorporating various proportions of GLP (0%, 20%, and 30%) as cement replacement. Ten mixture formulations, some of which also included sand-size crushed glass aggregate particles, were used to cast ten concrete slabs (1.5 × 2.5 × 0.25 m). Cylinders and prisms were also manufactured from the same batches at the time of casting for the measurement of compressive and splitting tensile strength, flexural strength, shrinkage, expansion, ultrasonic pulse velocity, volume of permeable voids, and chloride permeability. Core samples were drilled from the slabs at various ages for the same tests (except tensile and flexural), as well as for micro-structural examination. Results showed that strength gain was slower in GLP-bearing concrete up to 28 days, but at the age of 404 days all the mixtures exceeded the 40 MPa target and achieved about 55 MPa strength. Mixtures containing GLP also performed satisfactorily with respect to drying shrinkage and alkali reactivity, and there were indications that GLP reduces the chloride ion penetrability of the concrete, thereby reducing the risk of chloride induced corrosion of the steel reinforcement in concrete. The results demonstrated that GLP can be incorporated into 40 MPa concrete at dosage rates of

20–30% to replace cement without harmful effects. The use of GLP provides for considerable value-added utilization of waste glass in concrete and significant reductions in the production of green house gases by the cement industry.

Liu [29]

This research investigated the feasibility of using ground glass in self-compacting concrete (SCC). The ground glass was used as a partial replacement for both the cement and fine aggregate. The results show that to keep the filling ability constant, the inclusion of ground glass would require an increase in water/powder ratio and a reduction in superplasticizer dosage. These did not change the passing ability, but degraded the consistence retention and hardened properties such as strength but not to a prohibitive extent. This research concluded that SCC with satisfactory fresh properties can be produced by incorporating up to 104 kg/m3 ground glass, replacing about 10% cement and 10% sand, without the need for viscosity modifying agent (VMA).The successful completion of this study can lead to the application of ground glass in SCC, thus widening the types of additions available for SCC, saving landfills and reducing CO_2 emissions by the use of less cement and sand.

Limbachiya [30]

The paper reported the results of an experimental programme aimed at examining the performance of Portland-cement concrete produced with washed glass sand (WGS), as natural sand substitute by mass. The effects of up to 50% WGS on fresh, engineering and durability related properties were established and its suitability for use in a range of normal-grade concrete production assessed. WGS characteristics results showed that the post-container glass waste can be crushed to provide WGS of physical properties that satisfy the current requirements set in appropriate standards for natural sand for concrete. The density and water absorption of WGS was found to be lower than natural sand. The results for fresh concrete showed a reduction in workability of concrete with increase WGS proportion beyond 20% in the mix, although slump measurements remained within the allowable margin of ±25 mm. The mixes with high proportions of WGS were found to be less cohesive. Studies of hardened concrete properties, comprising bulk engineering properties (compressive cube and cylinder strength, flexural strength, modulus of elasticity, drying shrinkage) and durability (near surface absorption, alkali silica reaction) showed similar performance for concrete produced with natural aggregates and up to 15% WGS.

Schwarz et *al.* [31]

This paper reports the results of an investigation carried out to understand the influence of a fine glass powder on cement hydration. The pozzolanicity of the glass powder and a Class F fly ash for comparison was evaluated using strength activity index over a period of time, and a rapid electrical conductivity based method. Flame emission spectroscopy and electrical conductivity tests were used to quantify the alkali release from glass powder, and gain information on the rate of alkali release. It was found that the glass powder releases only a very small fraction of sodium ions into the solution. It was observed that the glass powder modified pastes show higher non-evaporable water contents than the plain paste and fly ash modified pastes, indicating that glass powder facilitates enhancement in cement hydration. An expression was developed for the change in non-evaporable water content as a result of enhancement in cement hydration and the hydration of the cement replacement material. The efficiency of any cement replacement material with age in the paste system can be quantified using this parameter. Based on this parameter, a 5% cement replacement with glass powder was found to be effective at the chosen water-to-cementing materials ratio (w/cm), whereas at higher replacement levels, the dilution effect dominates. A model to predict the combined degree of hydration of cement pastes incorporating more than one cementing material is outlined. The measured and predicted combined degrees of hydration agree well.

2.6 STEEL MAKING SLAG

Shi & Qian [32]

Steel slag is used as asphalt concrete aggregate in some countries. High free-CaO content in steel slag may cause volume expansion problems. The Ministry of Transportation of Ontario, Canada, banned the use of steel slag in asphalt concrete on provincial highways several years ago because of the expansion problem. A specialty steel slag cement, which is composed mainly of steel slag, blast furnace slag and Portland cement, was commercially marketed in China for more than 20 years and uses approximately 40% of the total steel slag production. This type of cement has the advantages of lower energy cost, higher abrasion resistance, lower hydration heat evolution and higher later strength development, but the disadvantage of longer setting time and lower early strength when compared with Portland cement. Steel slag cement can be used for general construction use, especially suitable for mass concrete and pavement applications due to its special features. The mineralogical composition of steel slag changes with its chemical composition. However, free-CaO content also increases with the basicity of steel slag. The C_3S content in steel slag is much lower than in Portland cement. Thus, steel slag can be regarded as a weak Portland cement clinker.

Activated steel slag cement

An activation process was invented to improve the properties of steel slag cement. The activation process decreases both the times of initial and final setting of Grade-325 steel slag cement, but no obvious effect on the times of setting of Grade-425 steel slag cement. The activation process does not increase the strength of Grade-425 cement as effectively as it does on Grade-325 steel slag cement. The 7-day and 28-day strengths of the activated Grade-425 steel slag cement are lower than those of activated Grade-325 steel slag cement.

2.7 COPPER SLAG

AlJabri et *al.* [33]

This paper reported on an experimental program to investigate the effect of using copper slag as a replacement of sand on the properties of high performance concrete (HPC). Eight concrete mixtures were pre- pared with different proportions of copper slag ranging from 0% (for the control mix) to 100%. Concrete mixes were evaluated for workability, density, compressive strength, tensile strength, flexural strength and durability. The results indicate that there is a slight increase in the HPC density of nearly 5% with the increase of copper slag content, whereas the workability increased rapidly with increases in copper slag percentage. Addition of up to 50% of copper slag as sand replacement yielded comparable strength with that of the control mix. However, further additions of copper slag caused reduction in the strength due to an increase of the free water content in the mix. Mixes with 80% and 100% copper slag replacement gave the lowest compressive strength value of approximately 80 MPa, which is almost 16% lower than the strength of the control mix. The results also demonstrated that the surface water absorption decreased as copper slag quantity increases up to 40% replacement; beyond that level of replacement, the absorption rate increases rapidly. Therefore, it is recommended that 40 wt% of copper slag can used as replacement of sand in order to obtain HPC with good strength and durability properties.

AlJabri et *al.* [34]

An experimental investigation was conducted to study the effect of using copper slag as a fine aggregate on the properties of cement mortars and concrete. Various mortar and concrete mixtures were prepared with different proportions of copper slag ranging from 0% (for the control mixture) to 100% as fine aggregates replacement. Cement mortar mixtures were evaluated for compressive strength, whereas concrete mixtures were evaluated for workability, density, compressive strength, tensile strength, flexural strength and durability. The results obtained for cement mortars revealed that all mixtures with different copper slag proportions yielded comparable or higher compressive strength than that of the control mixture. Also, there was more than 70% improvement in the compressive strength of mortars with 50% copper slag substitution in comparison with the control mixture. The results obtained for concrete indicated that there is a slight increase in density of nearly 5% as copper slag content increases, whereas the workability increased significantly as copper slag percentage increased compared with the control mixture. A substitution of up to 40–50% copper slag as a sand replacement yielded comparable strength to that of the control mixture. However, addition of more copper slag resulted in strength reduction due to the increase in the free water content in the mix. Also, the results demonstrated that surface water absorption decreased as copper slag content increases up to 50% replacement. Beyond that, the absorption rate increased rapidly and the percentage volume of the permeable voids was comparable to the control mixture. Therefore, it is recommended that up to 40–50% (by weight of sand) of copper slag can be used as a replacement for fine aggregates in order to obtain a concrete with good strength and durability requirements.

Khanzadi *et al.* [35]

This paper presented the results of a study undertaken to investigate the feasibility of using copper slag as coarse aggregates in high-strength concrete. The effects of replacing limestone coarse aggregate by copper slag coarse aggregate on the compressive strength, splitting tensile strength, and rebound hammer values of high-strength concretes were evaluated in this work. Concrete mixtures containing different levels of silica fume were prepared with water to cementitious materials ratios of 0.40, 0.35, and 0.30. The percentages of the cement replacements by silica fume were 0%, 6%, and 10%. The use of copper slag aggregate compared to limestone aggregate resulted in a 28-day compressive strength increase of about 10–15%, and a splitting tensile strength increase of 10–18%. It can be concluded from the results of this study that using copper slag as coarse aggregate in high-strength concrete is technically possible and useful.

Wei Wu et *al*. [36]

This study investigated the mechanical properties of high strength concrete incorporating copper slag as a fine aggregate and concluded that less than 40% copper slag as sand substitution can achieve a high strength concrete that comparable or better to the control mix, beyond which however its behaviors decreased significantly. The workability and strength characteristics were assessed through a series of tests on six different mixing proportions at 20% incremental copper slag by weight replacement of sand from 0% to 100%. The results indicated that the strength of the concrete with less than 40% copper slag replacement was higher than or equal to that of the control specimen and the workability even had a dramatic growth. The microscopic view demonstrated that there were limited differences between the control concrete and the concrete with less than 40% copper slag content. It also suggested that the determination of the copper slag replacement level should consider with the desired compressive strength of concrete.

Najimi *et al.* [37]

Sulfate attack was one of several chemical mechanisms of concrete deterioration. Exposure of concrete structures in the sulfate environments may lead to detrimental chemical, micro structural and physical changes in the concrete matrix, resulting in serious deteriorations and service life reduction. Partial replacement of cement with slag was one of the efficient methods for improving concrete resistance against sulfate attack. In this paper the performance of copper slag contained concrete in sulfate solution is investigated. In this regard, an experimental study including expansion measurements, compressive strength degradation and micro structural analysis were conducted in sulfate solution on concretes made by replacing 0%, 5%, 10% and 15% of cement with copper slag waste. The results of this study emphasized the effectiveness of copper slag replacement in improving the concrete resistance against sulfate attack.

2.8 FERROCHROMIUM SLAG

Zelic [38]

This paper presented the results of investigation related to both the properties of the ferrochromium slag and the standard physical and mechanical properties of Portland cement concrete pavements (PCCP) made with this slag as aggregate, according to the relevant Croatian standards. With a proper selection of slag as artificial aggregate, concrete pavements with compressive strengths, wear resistance and specific weight higher than in those from natural (limestone) aggregate in commercial Portland cement, type CEM II/B-S 42.5 (EN 197), can be made. The 28-day compressive strength of the concretes made with original unfractioned slag and with standard limestone as aggregates (w/c=0.64 and 350 kg/m3) reached the values of 57.00 MPa and 36.70 MPa, respectively. Volume stability, high volume mass, good abrasion resistance to wear and crushability make this reinforced slag concrete suitable for wearing courses of concrete pavements for traffic load classes 1 and 2 where carbonate stone material (limestone) mainly does not meet the Standard Technical Requirements for cement concrete slab pavements according to the relevant Croatian standard.

2.9 SILICA FUME

Mazloom et *al.* [39]

The results of experimental worked on short and long-term mechanical properties of high-strength concrete containing different levels of silica fume. The aim of the study was to investigate the effects of binder systems containing different levels of silica fume on fresh and mechanical properties of concrete. The work focused on concrete mixes having a fixed water/binder ratio of 0.35 and a constant total binder content of 500 kg/m3. The percentages of silica fume that replaced cement in this research were:

0%, 6%, 10% and 15%. Apart from measuring the workability of fresh concrete, the mechanical properties evaluated were: development of compressive strength, secant modulus of elasticity, strain due to creep, shrinkage, swelling and moisture movement. The results of this research indicated that as the proportion of silica fume increased, the workability of concrete decreased but its short-term mechanical properties such as 28-day compressive strength and secant modulus improved. Also the percentages of silica fume replacement did not have a significant influence on total shrinkage; however, the autogenous shrinkage of concrete increased as the amount of silica fume increased. Moreover, the basic creep of concrete decreased at higher silica fume replacement levels. Drying creep (total creep   basic creep) of specimens was negligible in this investigation. The results of swelling tests after shrinkage and creep indicate that increasing the proportion of silica fume lowered the amount of expansion. Because the existing models for predicting creep and shrinkage were inaccurate for high-strength concrete containing silica fume, alternative prediction models.

Razak & Wong [40]

A mathematical model was presented for estimating compressive strength of high-strength concrete incorporating pozzolanic materials, based on the strength of a control ordinary Portland cement (OPC) concrete made with similar mixture characteristics and curing history. In this study, metakaolin (MK) and silica fume (SF) were used as cement replacement materials at 5%, 10%, and 15% by mass. Water/ cementitious materials (w/cm) ratios varied from 0.27 to 0.33, and strength testing was conducted up to an age of 180 days. It was found that the strength of a pozzolanic mixture could be related to the strength of its equivalent control by a linear function. Key parameters involved in the model are the pozzolanic and dilution factors, which can be correlated to the pozzolan content in the mixture. The study concludes that the accuracy of the model increases with concrete age. At ages 28 days and above, 97% of the estimated strengths are within F 5% of the actual value.

2.10 METAKAOLIN

Kim *et al.* [41]

In order to evaluate and compare the mechanical properties and durability of concrete using metakaolin, the following tests were conducted on concrete specimens using various replacements of silica fume and metakaolin; mechanical tests such as compressive, tensile and flexural strength tests, durability tests like rapid chloride permeability test, immersion test in acid solution, repeated freezing and thawing test and accelerated carbonation test.

Strength tests revealed that the most appropriate strength was obtained for a substitution rate of metakaolin to binder ranging between 10% and 15%. It was observed that the resistance to chloride ion penetration reduced significantly as the proportion of silica fume and metakaolin binders increased. The fillers effect resulting from the fine powder of both binders was seen to ameliorate substantially the resistance to chemical attacks in comparison with ordinary concrete. Durability tests also verified that concrete using metakaolin bore most of the mechanical and durability characteristics exhibited by concrete using silica fume. The tests implemented in this study confirmed that metakaolin constitutes a promising material as a substitute for the cost prohibitive silica fume.

Khatib *et al.* [42]

The influence of incorporating ground granulated blast furnace slag (GGBS) and metakaolin (MK) on concrete strength was investigated. Portland cement was partially replaced with 0–80% GGBS and 0–20% MK. The water to cementitious materials ratio was maintained at 0.5 for all mixes. The incorporation of MK causes an increase in strength, especially during the early ages of curing. However, the use of GGBS in concrete reduces the strength during the first 28 days. Beyond 28 days, the strength increases with the presence of GGBS up to 60% replacement. The decrease in compressive strength during the early ages of curing of GGBS concrete is compensated by the inclusion of MK. The presence of MK in concrete containing GGBS does not cause a decrease in the long-term strength. The incorporation of up to 60% GGBS to partially replace PC in concrete causes an increase in long-term compressive strength and Ed. An increase in MK content in concrete up to 20% as partial substitution of PC increases the strength and Ed, especially during the early ages of hydration. The presence of MK in concrete containing GGBS causes an increase in strength during the early ages of hydration. This increase does not normally occur when GGBS is present in concrete before 28 days of curing.

2.11 SUMMARY OF LITERATURE REVIEW

The review of the literature directly related to the proposed study is summarized, as shown in Table 2.1 for each industrial by-product which is used in this thesis work.

Table 2.1 Summary of literature review

S.No.	AUTHOR	BY-PRODUCT USED	RESULTS
1.	Adolfsson *et al.* [1]	50% of LFS and 50% of GGBS	Compressive strength of 31.6 MPa after 28 days of LFS/GGBS mixtures which is higher than LFS
2.	Manso [2]	30% LFS as binder & 25%LFS as sand	Compressive strength of 19.45 MPa after 90 days and under durability test-favorable sodium sulphate test and unfavorable wetting–drying test
3.	Papayianni *et al.* [3]	50% High Calcium Fly-ash and 30% LFS as binder and EAF slag as aggregate	>70 MPa 28- day compressive strength, excellent abrasion resistance but freeze-thaw result showed considerable loss of material
4.	Siddique [16]	50% Class F fly ash	32.1 MPa compressive strength, 3.0 MPa Splitting strength, and 5.5 MPa flexural strength after one year and good abrasion resistance
5.	Jo *et al.* [17]	alkali-activated fly ash lightweight aggregate	Compressive strength of 26.47 MPa and good freeze–thaw resistance at 6.0% entrained air content
6.	Jiang *et al.* [18]	large volume of low quality fly-ash	Corrosion resistance of LVLQFA concrete in 5% Na2SO4 and 5% HCl solution is better than that of the control concrete
7.	Sahmaran *et al.* [20]	high lime fly ash (containing 10.07 % lime content) and low lime fly ash (containing 2.21% lime content)	40MPa and 33 MPa compressive strength at 28 days and improved workability
8.	Nochaiya *et al.* [21]	Fly ash and Silica fume	Higher compressive strength of 40.5 MPa and 41.0 MPa of 10FA5SF and 20FA10SF respectively

9.	Nazari & Riahi [11]	45% granulated blast furnace slag, TiO2 nanoparticles and SiO2 nanoparticles as binder	Improved compressive strength, tensile strength and flexural strength at < 4% TiO2 nanoparticles as binder
10	Nazari & Riahi [12]	45% granulated blast furnace slag, TiO2 nanoparticles and SiO2 nanoparticles as binder	Improved compressive strength, tensile strength and flexural strength at < 3% SiO2 nanoparticles as binder
11	Vejmelkova *et al.* [12]	56% BFS and 40% Metakaolin	Compressive strength of 67.7MPa in case of metakaolin blended cement & thaw resistance was satisfactory
12	Haha *et al.* [15]	alkali behaviour of BFS	50 to 80% increase of the compressive strength after 28 days.
13	Chidiac *et al.* [23]	10% Waste glass powder as binder and high and low density polyethylene pallets as sand replacement varying from 3%, 6% and 9%.	Compressive strength of 32MPa
14	Park *et al.* [24]	waste glass (amber, emerald green, flint, and mixed glass) as fine aggregates with 10% SBR latex	Compressive strength of 40 MPa and good workability
15	Taha *et al.* [25]	alike-silica-reaction which increases expansion when using glass powder	Using minimum low calcium ashes (Ca^{++}) and using Lithium compounds ASR expansion can be reduced
16	Juan M. Manso *et al.* [6]	50% EAF as coarse aggregate	Compressive strength of 43.8 MPa
17	Muhmood *et al.* [8]	20% ground granulated blast furnace slag with treated & untreated EAF slag	EAF slag does not decreases the compressive strength (58.6 MPa) beyond 20 days as compared to 58 MPa for the cement comprising of 20% untreated slag

2.12 GAPS IN LITERATURE

1. The replacement of cement by fly-ash and ladle furnace slag was done and its strength and durability was studied [3]. However in this thesis work it is proposed to use blast furnace slag along with the fly-ash and ladle furnace slag as substitution of cement for concrete production and analyze the strength and durability of concrete thus formed. This has not been done before.

2. No studies were reported on use of grinding chips of steel as aggregate. First time in this thesis work steel powder/scraps was used as substitution of fine aggregate. Electric arc furnace slag has already been used as a coarse aggregate in making of concrete [6-7].In this thesis work, electric arc furnace slag was used as fine aggregate. Waste glass powder can be used as fine aggregate when it is finer than 45 micrometer [23]. However in this thesis work it is proposed to use electric arc furnace slag along with the glass powder and steel powder/scrap as substitution of fine aggregate for concrete production and analyze the strength and durability of concrete thus formed. This has not been done before.

3. Also during this study, the mixture of various by-products (BFS, LFS, FA, EAF, Glass and Steel powder/Scrap) will also be tested for Compressive Strength, Tensile Strength and Durability.

2.13 OBJECTIVE OF THE PRESENT WORK

The objective of this thesis work is to find the optimal usage of industrial by-products (Blast furnace slag, Ladle furnace slag, Fly-ash, Electric arc furnace slag, Glass powder and Steel powder/Scrap) as substitutes to cement and aggregates. The concrete so made was evaluated for strength and durability and the results are analyzed using Analysis of Variance (ANOVA) and followed by optimization of the process parameters.The water to cement ratio is the ratio of the weight of water to the weight of cement used in a concrete mix and has a significant influence on the quality of concrete produced. The experimental program was designed for water to cement ratios varying from 0.40 to 0.50. Binder was replaced by industrial by-products varying from 10% to 30% and fine aggregate was replaced by industrial by-products varying from 5% to 15%.

Two replacements were done in this experimental work.

1. Binder was replaced by industrial by-products such as-

1. Blast furnace Slag (BFS)
2. Fly-ash (FA)
3. Ladle furnace slag (LFS)

2. Fine aggregate was replaced by industrial by-products such as-

1. Glass powder (GP)
2. Electric arc furnace slag (EAFS)
3. Steel powder/Scrap (SP/S)

CHAPTER 3 METHODLOGY & EXPERIMENTAL WORK

3.0 GENERAL

The full factorial design is referred to as the technique of defining and investigating all possible conditions in an experiment involving multiple factors while the fractional factorial design investigates only a fraction of all the combinations. Although these approaches are widely used, they have certain limitations: they are inefficient in time and cost when the number of the variables is large; they require strict mathematical treatment in the design of the experiment and in the analysis of results; the same experiment may have different designs thus produce different results; further, determination of contribution of each factors is normally not permitted in this kind of design. The Taguchi method was proposed to overcome these limitations by simplifying and standardizing the fractional factorial design. The methodology involves identification of controllable and uncontrollable parameters and the establishment of a series of experiments to find out the optimum combination of the parameters which has greatest influence on the performance and the least variation from the target of the design. The effect of various parameters (Water to Cement Ratio, Perchantage of by-product used as binder, Perchantage of by-product used as fine aggregate, Binder, Fine aggregate, Curing days) were also be studied using parameterization approach developed by Taguchi [50]. Taguchi method will be used to verify the optimal mixture design.

3.1 TAGUCHI METHOD

Taguchi method was developed as a process optimization technique by Genichi Taguchi during the 1950s. Taguchi's approach to parameter design provides the design engineer with a systematic and efficient method for determining near optimum design parameters for performance and cost [51]. The processes involved in Taguchi method are shown in Figure 3.1. Flow graph defines the various steps of Taguchi method applying to find out the optimum mixture design [50].

3.2 PROCEDURE OF EXPERIMENTAL DESIGN

The essential steps in the procedure of Taguchi method are as follows [50].

1. Establishing the objective function.
2. Selection of factors which needs to be evaluated.
3. Identifying the uncontrollable factors as well as test conditions.
4. Selecting the number of levels for the controllable and uncontrollable factors.
5. Calculating the total degree of freedom which are needed
6. Selecting the appropriate Orthogonal Array (OA)
7. Assigning of factors to columns.
8. Executing the experiments according to trial conditions in the array.
9. Analyzing the results.
10. Confirmation of experiments

3.3 SELECTION OF PARAMETER/FACTORS

The determination of factors which needs to be investigated depends on the responses of interest. The factors that affect the responses were identified using several methods such as brainstorming, cause and effect analysis and flowcharting. The minimum degree of freedom required in the experiment is the sum of all the degrees of freedom of factors. In the present experiment setup**,** there are six factors varied at 3-level were chosen through pilot study. Taguchi design were used for the design of experiment because it reduces the number of iterations and used to optimize the known parameter. The following Parameter/Factors are proposed to be used for experiment are shown in Table 3.1.

3.4 DEGREE OF FREEDOM (dof)

The total degree of freedom required for the entire experimentation is determined by the number of factors, their interactions and level for factors. The degree of freedom for each factor is given by the number of levels minus one.

dof for each factor = k-1 ………………………………………………………….. (3.1)

Where k is the number of level for each factor.

The number of dof for factors A, B, C, D, E, F and G as shown in Table 3.1 are two. The total dof for the experiment is explained in Table 3.2. As the dof required for the experiment is 12; the orthogonal array (OA) to be used should have more than 12 dof.

The most suitable orthogonal array which can be used for this experiment is L18, which has 17 dof assigned to its various columns**.** The additional five dof were used to measure the random error.

3.5 ORTHOGONAL ARRAY

The Taguchi method utilizes orthogonal arrays from design of experiments theory to study a large number of variables with a small number of experiments. The experimental design was completed using the Taguchi's fractional factorial experiments (FFEs). Using orthogonal arrays significantly reduces the number of experimental configurations to be studied. Furthermore, the conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the control factors and their settings. Orthogonal array is derived from factorial design of experiment by a series of very sophisticated mathematical algorithms including combinatories, finite fields, geometry and error-correcting codes [50]. Orthogonal array plays a critical part in achieving the high efficiency of the Taguchi method. The Orthogonal array is constructed in a statistically independent manner. Within each column, number of occurrences of each level is equal and for each level within one column, each level within any other column will occur an equal number of times as well. Then, the columns are called orthogonal to each other. Orthogonal array is available with a variety of factors and levels in the Taguchi method. Since each column is orthogonal to the others, if the results associated with one level of a specific factor are much different at another level, it is because changing that factor from one level to the next has strong impact on the quality characteristic being measured. Since the levels of the other factors are occur an equal number of times for each level of the strong factor, any effect by these other factors will be ruled out [50]. The selection of orthogonal array depends on:

1. The number of factors and interactions of interest
2. The number of levels for the factor of interest

The most suitable orthogonal array which can be used for this experiment is L18 and experimental design of L18 is shown in Table 3.4**.** The 18 experimental designs represent the set of values of input process parameters with which particular experiment is to be conducted. The total 18 experiment were performed with repetition in order to maximize or minimize the effect of uncontrollable factors for each combination of all input parameters.

3.6 OBJECTIVE FUNCTION (RESPONSES)

The objective of the study is to evaluate the effect of water to cement ratio, perchantage of by-product used as binder, perchantage of by-product used as fine aggregate, type of by-product as a binder used, type of by-product used as a fine aggregate used and curing days on the compressive strength, tensile strength and durability of concrete.

3.6.1 Compressive Strength

The maximum load which the cubes were able to take before failure was noted and corresponding strength was reported as the compressive strength. Compressive strength is the capacity of a material or structure to withstand axially directed pushing forces. When the limit of compressive strength is reached, materials are crushed. By definition, the compressive strength of a material is that value of uniaxial compressive stress reached when the material fails completely.

Compressive strength = $\frac{P}{A}$ ……………………………………………………… (3.2)

Here P = Maximum load applied to the specimen (kN)

A= Cross section area (mm^2)

3.6.2 Splitting Tensile Strength

The tensile strength of a material is the maximum amount of tensile stress that it can be subjected to before failure. The maximum load applied in breaking a tensile test piece divided by the original cross-sectional area of the test piece. In case of diagonal splitting, tensile strength is determined as:

Tensile strength = 0.5187 * ($\frac{P}{S^2}$) …………………………………………… (3.3)

Here P = Failure load (kN)

S= Side of cube (mm)

3.6.3 Durability (Water Permeability Test)

Durability is defined as the capability of concrete to resist weathering action, Chemical attack and abrasion while maintaining its desired engineering properties. It normally refers to the duration or life span of trouble-free performance. Different concretes require different degrees of durability depending on the exposure environment and properties desired. For example, concrete exposed to tidal seawater will have different requirements than indoor concrete. In the present work water permeability of concrete was measured using the concept of depth penetrated.

3.7 MEASURING EQUIPMENT USED

The measurement method for each response is described below.

3.7.1 Automatic Compression Testing Machine

The Automatic Compression Testing Machine has all features of Micro Controller based Compression Testing Machine. The machine is available in 500kN, 1000kN, 2000kN, 3000kN ranges with an automatic load release facility, a facility for transmission of data to the serial port of a computer placed within 200 meters of the loading unit. It consist RS-485 to RS-232 convertor which converts data transmitted by the digital head to a form recognized by the computer. The unit comprises of loading unit and pumping unit. The loading unit is of fully welded construction having a cross head, base and solid side plates. The hydraulic jack is fixed to the base. The platens of the machine are hardened, ground and polished. The upper platen is provided with self-aligning action. To facilitate testing of various size specimens, suitable size spacers are provided. The pumping unit has a two-speed hydraulic motor driven pump and a bonded strain gauge based pressure transducer. The set up of ACTM is shown in Figure 3.2 and compute the compressive strength and split tensile strength of concrete [53].

Specification of Automatic Compression Testing Machine:

1. Made by AIMIL Ltd, India
2. Linear Variable Differential Transducer attachment
3. 3000 KN Capacity
4. Serial no. 09149
5. CAT no. AIM-320E-FA

3.7.2 Universal Testing Machine

A universal testing machine, as shown in Figure 3.3 is used to test the split tensile strength and compressive strength of materials. The specimen is placed in the machine between the grips and an extensometer if required can automatically record the change in gauge length during the test. If an extensometer is not fitted, the machine itself can record the displacement between its cross heads on which the specimen is held. However, this method not only records the change in length of the specimen but also all other extending / elastic components of the testing machine and its drive systems including any slipping of the specimen in the grips. Once the machine is started it begins to apply an increasing load on specimen. Throughout the tests the control system and its associated software record the load and extension or compression of the specimen [54].

Specification of Universal Testing Machine:

1. Made by HUNG Ta Instrument co. Ltd, Japan
2. Fully computerised, Servo controlled machine
3. 1000 KN Capacity
4. Serial no. 2159

3.7.3 Water Penetration Test

Each water reservoir shall be calibrated using water under 1.38-MPa pressure. A small rubber hose is fitted by means of a threaded adapter to the bleeder valve in the line between the reservoir and the specimen container. The valve to the container is closed and the reservoir filled with water, as shown schematically in Figure 3.4. Pressure at 1.38 MPa is applied; all bleeder valves are opened to remove entrapped air, and are immediately closed when water issues from them. The 1.38-MPa pressure is then released and the reservoir is again filled with water to a point above the zero mark on the graduated scale . The pressure is again applied and the bleeder valve is opened slowly and quickly closed when the water level in the reservoir and gage glass is at the zero mark on the scale. Water then is removed from the system and caught in 500cm^3 increment in a graduated cylinder. After each 500cm^3 increments the level in the gage glass is read on the scale. The calibration constant for the reservoir is calculated from the reading and is expressed in cm^3 per unit length on the scale.

Specification of Water Penetration Testing Machine:

1. Made by AIMIL Ltd, India
2. Serial no. 05060
3. CAT no. AIM-384

3.8 ANALYSIS OF RESULTS

3.8.1 Analysis of variance

ANOVA is a mathematical technique which breaks total variation down into accountable sources; total variation is decomposed into its appropriate components. ANOVA is a statistically based decision tool for detecting any differences in average performance of groups of items tested. Analysis of variation (ANOVA) will be the statistical method used to interpret experimental data and make necessary decisions.

ANOVA is very useful for revealing the level of significance of influence of factor(s) or interaction of factors on a particular response. It separates the total variability of the response (sum of squared deviations about the grand mean) into contributions rendered by each of the parameter/ factor and the error. Thus

$$SS_T = SS_F + SS_E \qquad \text{.................. (1)}$$

Where, $$SS_T = [\sum_{i=1}^{n} Y_i^2] - (\frac{T2}{N}) \qquad \text{................ (2)}$$

SS_T= Total sum of squared deviations about the mean.

Y_i = Mean response for *ith* experiment.

T = Sum of all observations

N= Total number of observation

SS_F Sum of squared deviations due to each factor.

SS_E Sum of squared deviations due to error

In the ANOVA table mean square deviation is defined as:

$$MS = \frac{SS}{DF} \qquad \text{............. (3)}$$

Where, SS= Sum of squared division

DF= Degree of freedom

3.8.2 Signal-to-noise ratio

The first concept of Taguchi that must be discussed is what he refers to as ‘‘noise factors”. Noise factors are viewed as the causes of variability in performance, including why products fail. The parameters that influence the output can be categorized into two classes, namely controllable (or design) factors and uncontrollable (or noise) factors. Controllable factors are those factors whose values can be set and easily adjusted by the designer. The control factors that may contribute to reduced variation can be quickly identified by looking at the amount of variation present in response [51]. For this experimental work, response characteristics have given in the Table 3.3. Uncontrollable factors are the sources of variation often associated with operational environment. The best settings of control factors as they influence the output parameters are determined through experiments. The objective is to select the best combination of control parameters so that the product or process is most robust with respect to noise factors. A noise factor is anything that causes a measurable product or process characteristic to deviate from its target value. Target values may be [51]:

Smaller is better: choose when goal is to minimize the response.

The S/N ratio can be calculated as given in Eq. (1) for smaller the better.

$$S/N = -10 * \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} Y_i^2\right) \quad \ldots\ldots (3.7)$$

Larger is better: choose when goal is to maximize the response.

The S/N ratio is calculated as given in Eq. (2) for larger the better.

$$S/N = -10 * \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} \frac{1}{Y_i^2}\right) \quad \ldots\ldots (3.8)$$

Nominal is better: choose when goal is to target the response and it is required to base the S/N ratio on standard deviations only.

The S/N ratio is calculated as given in Eq. (3) for smaller the better.

$$S/N = -10*\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n} (Y_i - Y_0)\right) \quad \ldots\ldots (3.9)$$

Where in Eqs. (1)– (3), Y shows the measured value of each response.

Here n is the number of tests in a trial (noise of repetitions regardless of noise levels)

$\sum_{i=1}^{n} Y_i$ = summation of all response values under each trial

Noise factors can be classified into three groups:

1. External noise factors: sources of variability that come from outside the product,
2. Unit-to-unit noise: due to the fact that no two manufactured components or products are ever exactly alike,
3. Internal noise: due to deterioration, aging, and wear incurred in storage and use.

3.9 EXPERIMENTAL PROCEDURE

The experimental procedure was designed to study the effect of replacement of cement and sand by various industrial by products. The material used for the casting of concrete samples along with the testing procedures is described herewith.

3.9.1 Materials

a) Cement: The cement used was Pozzolanic Portland cement (fly-ash based) as shown in Figure 3.5 (a). It was tested in laboratory for its properties as per Indian standards. The physical properties determined are shown in Table 3.5. The Cement used conforms to IS 1489 (part -1) 1991 on the basis of its determined characteristics.

b) Fine Aggregate: The sand used for the experiment programme was locally procured and conforms to Indian Standard Specification IS: 383-1970 as shown in Figure 3.5 (b). The sand is first sieved through 4.75 mm to remove any particles greater than 4.75. Physical Properties of the fine aggregate used in the experimental work are tabulated in Table 3.6. The fine aggregate were sieved through a set of sieves as shown in Table 3.9. The fine aggregate belonged to grading zone III.

c) Coarse Aggregates: Locally available coarse aggregates were used in the present study. The material which is retained on BIS test sieve no. 480 is termed as a coarse aggregate. The broken stone is generally used as a coarse aggregate. The nature of work decides the maximum size of the coarse aggregate to be used. Locally available coarse aggregate having the size of 20 mm and 10 mm were used in present work as shown in Figure 3.5 (d & e) respectively. Physical properties of 20mm and 10 mm aggregates are determined in laboratory and shown in Table 3.7 and Table 3.8 respectively. The aggregate were tested as per Indian Standard Specification IS: 383-1970. Sieve analysis of 20 mm and 10 mm coarse aggregate are tabulated in Table 3.10 and Table 3.12 respectively.

d) Super plasticizer: Conplast- SP430, a concrete superplasticizer based on Sulphonated Naphthalene Polymer as shown in Figure 3.5 (c) was used as a water-reducing admixture and to improve the workability of concrete. Conplast SP430 was specially formulated to give high water reductions up to 25% without loss of workability or to produce high quality concrete of reduced permeability. Conplast SP430 is non-toxic. A dose of 0.5%, 0.75% and 1% of Conplast SP430 super plasticizer by weight of binding material, was used for reducing the quality of water for the same workability. Physical characteristics of superplasticizer are shown in Table 3.11.

e) Water: Ordinary tap water was used for preparing of concrete specimens and also for curing for a specific period.

f) Blast furnace slag: Blast furnace slag as shown in Figure 3.6 (a) for the design of mixes in the present work was obtained from Quality Polytech, Karnataka (Maharashtra). The physical properties and chemical composition of blast furnace slag is mentioned in Table 3.13. These results were obtained from testing carried out at the Matter Lab located at Thapar University, Patiala. Energy dispersive X-ray spectroscopy test (EDAX) and scanning electron microscopy test (SEM) were used to obtain the chemical properties of blast furnace slag. SEM micrography of blast furnace slag is shown in Figure 3.13 (a).

g) Ladle furnace slag: Ladle furnace slag as shown in Figure 3.6 (b) for the design of mixes in the present work was obtained from Laxmi Steel Rolling Mills, Ludhiana (Punjab). The physical properties and chemical composition of ladle furnace slag is mentioned in Table 3.13. These results were obtained from testing carried out at the Matter Lab located at Thapar University, Patiala. Energy dispersive X-ray spectroscopy test (EDAX) and scanning electron microscopy test (SEM) were used to obtain the chemical properties of ladle furnace slag. SEM micrography of ladle furnace slag is shown in Figure 3.13 (b).

h) Fly-ash: Fly-ash as shown in Figure 3.6 (c) for the design of mixes in the present work was obtained from Guru Gobind Singh Super Thermal Plant, Ropar (Punjab). The physical properties and chemical composition of fly-ash are mentioned in Table 3.13. These results were obtained from testing carried out at the Matter Lab located at Thapar University, Patiala. Energy dispersive X-ray spectroscopy test

(EDAX) and scanning electron microscopy test (SEM) were used to obtain the chemical properties of fly-ash. SEM micrography of fly-ash is shown in Figure 3.13 (c).

i) Glass powder: Glass powder as shown in Figure 3.7 (b) for the design of mixes in the present work was obtained from Vikas Minerals, Bareilly (Uttar Pradesh). The physical properties and chemical composition of glass powder are mentioned in Table 3.14. These results were obtained from testing carried out at the Matter Lab located at Thapar University, Patiala. Energy dispersive X-ray spectroscopy test (EDAX) and scanning electron microscopy test (SEM) were used to obtain the chemical properties of glass powder. SEM micrography of glass powder is shown in Figure 3.13 (d).

j) Electric arc furnace slag: Electric arc furnace slag as shown in Figure 3.7 (a) for the design of mixes in the present work was obtained from Laxmi Steel Rolling Mills, Ludhiana (Punjab). The physical properties and chemical composition of Electric arc furnace slag are mentioned in Table 3.14. These results were obtained from testing carried out at the Matter Lab located at Thapar University, Patiala. Energy dispersive X-ray spectroscopy test (EDAX) and scanning electron microscopy test (SEM) were used to obtain the chemical properties of electric arc furnace slag. SEM micrography of electric arc furnace slag is shown in Figure 3.13 (e).

k) Steel powder & Steel scrap: Steel powder as shown in Figure 3.7 (c) for the design of mixes in the present work was obtained from Eastman Impacks, Ludhiana (Punjab) and Steel scraps as shown in Figure 3.7 (d) from Mechanical workshop of Thapar University, Patiala (Punjab).

3.10 CONCRETE MIX DESIGN

Standard concrete mixes were designed for three water to cement ratio of 0.40, 0.45 and 0.50 based on Indian standard recommended guidelines IS: 10262:2009. Design mix concrete cubes of size 150mm were cast and cured for specified period of time. The quantity of material for each concrete mix designed was tabulated in Table 3.15.
Test of compressive strengths, splitting tensile strength and water penetration depth were conducted on the blocks based on mentioned concrete mix design at 7days and 28 days period. The test results of compressive strength, splitting tensile strength and water penetration depth are shown in Table 3.16 as per IS 10262: 2009.

3.11 CONCRETE MIX DESIGN PROPORTION

The proportioning of mixes for various replacements by the industrial by-products, as per the L18 design, was carried out using two different approaches. The first approach a direct partial perchantage replacement in the design mix was done, whereas in the second approach the quantities of material were calculated considering the effect of variable specific gravities of the original material and its placement.

The mix proportions for various trials using both approaches are tabulated in Tables 3.17 and 3.18 respectively.

3.12 CASTING OF SPECIMEN

For each concrete mix 6 cubes of size 150 mm x 150 mm x 150 mm corresponding to above designed mix proportions were cast for testing at 7 days, 28 days and 56 days curing. For casting as shown in Figure 3.8, all the mould were cleaned and oiled properly. These were securely tightened to correct dimension before casting. Care was taken that there is no gaps left from where there is any possibilities of leakage out of slurry. Careful procedure was adopted in the batching, mixing and casting operation. The concrete mixture was prepared by hand mixing on a water tight platform. On the water tight platform, the coarse and fine aggregate were mixed thoroughly. To this mixture, the cement and industrial by-products were added. These were mixed to uniform colour. Then water was added carefully so that no water was lost during mixing. Clean and oiled moulds for each category were then placed on the vibrating table respectively and filled in three layers. Vibrations were stooped as soon as cement slurry appeared on the top surface of the mould. The casting of cubes was carried out as per IS 10086:1982.

3.13 CURING OF SPECIMEN

The specimens were allowed to remain in the steel moulds for the first 24 hours at the ambient conditions. After that these were demoulded as shown in Figure 3.9 (a) with care so that no edge was broken. As per the curing days of 7 days, 28 days and 56 days, each set is kept in water tank for curing as shown in Figure 3.9 (b). The ambient temperature for curing was 27 ± 2 ºC. Curing is the process of controlling the rate and extent of moisture loss from concrete during cement hydration.

3.14 TESTING OF SPECIMENS

Concrete specimens were tested after the curing period of 7 days, 28 days and 56 days as per Indian Standards and Cement specimens were casted after the curing period of 28 days. Compressive strength, Tensile strength and durability test are conducted on casting cubes as per their curing period.

3.14.1 Compressive strength

Cubical specimen of size 150 mm were cast for conducting compressive strength test for each mix. The compressive strength test was carried out as per IS 516:1979 at the end of 7 days, 28 days and 56 days of curing. The compressive strength of any mix was taken as the average of strength of three cubes. Compressive strength was tested on an automatic compression testing machine (3000KN capacity) as per procedure laid down in IS 516:1979 as shown in Figure 3.10. A uniform rate of 5kN/Sec was maintained throughout of the testing of each specimen.

3.14.2 Tensile strength

Cubical specimen of size 150 mm were cast for conducting tensile strength test for each mix. The tensile strength test was carried out as per IS 5816:1970 at the end of 7 days, 28 days and 56 days of curing. The tensile strength of any mix was taken as the average of strength of two cubes. Tensile strength was tested on a universal testing machine (1000KN capacity) as per procedure laid down in IS 5816:1970 as shown in Figure 3.11.

3.14.3 Durability (Water permeability test)

Cubical specimen of size 150 mm were cast for conducting water permeability test for each mix. The water permeability test was carried out as per Denmark standard DIN-1048 at the end of 7 days, 28 days and 56 days of curing. The water permeability test of any mix was taken as a average of three cubes. Durability of cubical specimen was tested on a water permeability test apparatus as per procedure laid down in DIN-1048 as shown in Figure 3.12**.** In water permeability test each water reservoir shall be calibrated using water under 1.38-MPa pressure. In the present work water permeability of concrete was measured using the concept of depth penetrated.

Table 3.1 Parametric factors

S. No.	Factor Designation	Parametric Factors	Units	Levels		
				I	II	III
1.	A	Water to Cement Ratio	Fraction	0.40	0.45	0.50
2.	B	Perchantage of by-product used as binder	Perchantage of total cement content	10%	20%	30%
3.	C	Perchantage of by-product used as fine aggregate	Perchantage of total fine aggregate	5%	10%	15%
4.	D	Binder	Kg/m^3	Blast furnace slag	Fly-ash	Ladle furnace slag
5.	E	Fine aggregate	Kg/m^3	Glass powder	Electric arc furnace slag	Steel powder
6.	F	Curing time	Days	7	28	56

Table 3.2 Degree of freedom

Factor	A	B	C	D	E	F	Total
Degree of freedom	2	2	2	2	2	2	12

Table 3.3 Response Characteristics

Response name	Response type	Units
Compressive strength	Higher the better	MPa
Tensile strength	Higher the better	MPa
Water Permeability (Penetration depth)	Lower the better	MM

Table 3.4 L-18 Array using six parameters at three levels

S.No.	Water to Cement ratio	By-product as a replacement of Binder (Percent)	By-product as a replacement of Fine aggregate (Percent)	By-product used as a replacement of Binder	By-product used as a replacement of Fine aggregate	Curing Time (Days)
1	0.40	10%	5	GGBFS	Glass Power	7
2	0.40	20%	10	FLY-ASH	EAFS	28
3	0.40	30%	15	LFS	Steel Powder	56
4	0.45	10%	5	FLY-ASH	EAFS	56
5	0.45	20%	10	LFS	Steel Powder	7
6	0.45	30%	15	GGBFS	Glass Power	28
7	0.50	10%	10	GGBFS	Steel Powder	28
8	0.50	20%	15	FLY-ASH	Glass Power	56
9	0.50	30%	5	LFS	EAFS	7
10	0.40	10%	15	LFS	EAFS	28
11	0.40	20%	5	GGBFS	Steel Powder	56
12	0.40	30%	10	FLY-ASH	Glass Power	7
13	0.45	10%	10	LFS	Glass Power	56
14	0.45	20%	15	GGBFS	EAFS	7
15	0.45	30%	5	FLY-ASH	Steel Powder	28
16	0.50	10%	15	FLY-ASH	Steel Powder	7
17	0.50	20%	5	LFS	Glass Power	28
18	0.50	30%	10	GGBFS	EAFS	56

Table 3.5 Physical properties of Cement

S.No.	Characteristics	Value obtained in Laboratory	Value as per IS-1489 (part -1) 1991
1.	Specific gravity	3.10	3.15
2.	Fineness(% retained on90µm Sieve)	1	<10
3.	Standard consistency (%)	34	----
4.	Initial setting time (min)	130	30(min.)
5.	Final setting time (min)	240	600(max.)
6.	Compressive strength (N/mm^2)	3 days = 16.22 7 days = 22.31 28 days = 33.50	16.00 22.00 33.00

Table 3.6 Physical properties of Fine aggregate

S.No.	Characteristics	Value obtained in Laboratory
1.	Specific gravity	2.50
2.	Fineness Modulus	1.992
3.	Water absorption	0.8%
4.	Grading Zone	III
5.	Unit Weight (kN/m^3)	16.20

Table 3.7 Physical properties of Coarse aggregate (20mm)

S.No.	Characteristics	Value obtained in Laboratory
1.	Specific gravity	2.62
2.	Fineness Modulus	6.94
3.	Water absorption	1.1%
4.	Oven dry Specific gravity	2.65
5.	Unit Weight (kN/m^3)	14.68

Table 3.8 Physical properties of Coarse aggregate (10mm)

S.No.	Characteristics	Value obtained in Laboratory
1.	Specific gravity	2.56
2.	Fineness Modulus	6.16
3.	Water absorption	1.0%
4.	Oven dry Specific gravity	2.59
5.	Unit Weight (kN/m^3)	16.05

Table 3.9 Sieve analysis of Fine aggregate

S.No.	Size of Sieve	Mass retained (in grams)	Percentage retained (%)	Percentage passing (%)	Cumulative percentage retained	Zone
1.	4.75 mm	85.5	8.55	91.45	8.55	I/II/III
2.	2.36 mm	35.5	3.55	87.90	12.10	I/I/III
3.	1.18 mm	54.0	5.40	82.50	17.50	I/I/III
4.	**600 µ**	**66.0**	**6.60**	**75.90**	**24.10**	**III/IV**
5.	300 µ	174.5	17.45	58.90	41.55	II
6.	150 µ	538.5	53.85	4.60	95.40	I
7.	Pan	46.0	4.60	------	-------	------
	Total	1000		SUM=∑C	199.20	

F.M.=∑C/100=199.20/100=1.992

Table 3.10 Sieve analysis of coarse aggregate (20mm)

S.No.	Size of Sieve	Mass retained (in grams)	Percentage retained (%)	Percentage passing (%)	Cumulative percentage retained
1.	20 mm	4.00	0.13	99.87	0.13
2.	10mm	2832.50	94.42	5.45	94.55
3.	4.75 mm	146.50	4.88	0.57	99.43
4.	2.36 mm	0	0	0	0
5.	1.18 mm	0	0	0	0
6.	600 µ	0	0	0	0
7.	300 µ	0	0	0	0
9.	Pan	17.00	0.57	----	----
	Total	3000		SUM=∑C	194.11

F.M.=∑C+500/100=694.11/100=6.94

Table 3.11 Technical data of Superplasticizer

S. No.	Characteristics	Value
1.	Colour	Dark Brown liquid
2.	Specific gravity @ 30˚ C	1.22 to 1.225
3.	Air entrainment	Maximum 1 %

Table 3.12 Sieve analysis of coarse aggregate (10mm)

S.No.	Size of Sieve	Mass retained (in grams)	Percentage retained (%)	Percentage passing (%)	Cumulative percentage retained
1.	20 mm	0.00	0	0	0
2.	10mm	828.00	27.60	72.40	27.60
3.	4.75 mm	1827.50	60.92	11.48	88.52
4.	2.36 mm	0	0	0	0
5.	1.18 mm	0	0	0	0
6.	600 µ	0	0	0	0
7.	300 µ	0	0	0	0
8.	150 µ	0	0	0	0
9.	Pan	344.50	11.48	------	-------
	Total	3000		SUM=∑C	116.12

F.M.=∑C+500/100=616.12/100=6.16

Table 3.13 Physical properties and Chemical composition of by-products used as a Binder by SEM and EDAX

Ground Granulated Blast Furnace Slag		Ladle Furnace slag		Fly-ash	
Fineness (% retained at 90µm)	2	Fineness(% retained at 90µm)	57	Fineness (% retained at 90µm)	26
Specific gravity	2.93	Specific gravity	2.5	Specific gravity	2.0
CaO	21.8	CaO	77.93	CaO	0.44
SiO_2	43.3	SiO_2	3.29	SiO_2	41.20
Al_2O_3	16.1	Al_2O_3	2.18	Al_2O_3	23.29
MgO	10.1	MgO	4.34	MgO	0.95
Fe_2O_3	1.1	Fe_2O_3	0.00	Fe_2O_3	2.84
SO_3	0.5	SO_3	2.06	SO_3	---
K_2O	2.8	K_2O	2.68	K_2O	1.26
Na_2O	0.4	P_2O_5	2.60	Na_2O	---
TiO_2	0.9	TiO_2	---	TiO_2	1.65

Table 3.14 Physical properties and Chemical composition of by-products used as a Fine Aggregate by SEM and EDAX

Glass Powder		Electric Arc Furnace slag	
Fineness (% retained at 90μm)	0.50	Fineness(% retained at 90μm)	9
Specific gravity	2.47	Specific gravity	3.37
CaO	5.16	CaO	29.02
SiO_2	42.17	SiO_2	16.52
Al_2O_3	0.68	Al_2O_3	6.34
MgO	2.25	MgO	2.36
Fe_2O_3	0.00	Fe_2O_3	25.08
K_2O	0.32	$\sum TiO_2 + SO_3 + MnO + Cr_2O_3$	3.14
Na_2O	8.13	P_2O_5	0.64

Table 3.15 Concrete mix for Water to Cement ratio (W/C) = 0.40, 0.45 and 0.50

Material	**(kg/m^3) For W/C =0.40**	**(kg/m^3) For W/C =0.45**	**(kg/m^3) For W/C =0.50**
Cement	425	400	370
Water	170	180	185
Sand	413.5	512.5	532.5
Coarse aggregate (20 mm)	668.1	613.08	607.84
Coarse aggregate (10 mm)	652.8	601.6	593.92

Table 3.16 Results of Standard Concrete mix for W/C ratio = 0.40, 0.45 and 0.50

Concrete mix	**For W/C =0.40**		**For W/C =0.45**		**For W/C =0.50**	
	7 Days	**28 Days**	**7 days**	**28 Days**	**7 Days**	**28 Days**
Compressive Strength (N/mm^2)	29.03	40.92	27.71	36.33	20.3	31.52
Splitting Tensile Strength (N/mm^2)	2.54	3.59	2.31	3.01	2.01	2.78
Water Penetration Depth	40 mm	30 mm	45 mm	35 mm	50 mm	42 mm

Table 3.17 Concrete Mix Design Proportion without using specific gravity of by-product (Approach -1)

TRAIL NO.	WATER TO CEMENT RATIO	WATER (kg/m³)	BINDER (kg/m³)			FINE AGGREGATE (kg/m³)			COARSE AGGREGATE (kg/m³)		SUPER-PLASTICIZER (PERCHANTAGE OF WEIGHT OF CEMENT)
			CEMENT	REPLACEMENT MATERIAL	AMOUNT	SAND	REPLACEMENT MATERIAL	AMOUNT	20 MM	10 MM	
1	0.40	170	382.5	BLAST FURNACE SLAG	42.5	392.8	GLASS POWDER	20.7	668.1	652.8	1.0
2	0.40	170	297.5	FLY-ASH	127.5	372.2	GLASS POWDER	41.4	668.1	652.8	1.5
3	0.40	170	340	FLY-ASH	85	372.2	ELECTRIC ARC FURNACE SLAG	41.4	668.1	652.8	1.0
4	0.40	170	382.5	LADLE FURNACE SLAG	42.5	351.5	ELECTRIC ARC FURNACE SLAG	62.03	668.1	652.8	1.0
5	0.40	170	297.5	LADLE FURNACE SLAG	127.5	351.5	STEEL POWDER	62.03	668.1	652.8	1.5
6	0.40	170	340	BLAST FURNACE SLAG	85	392.8	STEEL POWDER	20.7	668.1	652.8	1.0
7	0.45	180	320	LADLE FURNACE SLAG	80	461.3	STEEL POWDER	51.3	613.1	601.6	0.0
8	0.45	180	320	BLAST FURNACE SLAG	80	435.6	ELECTRIC ARC FURNACE SLAG	76.9	613.1	601.6	0.0
9	0.45	180	280	BLAST FURNACE SLAG	120	435.6	GLASS POWDER	76.9	613.1	601.6	0.75
10	0.45	180	280	FLY-ASH	120	486.8	STEEL POWDER	25.6	613.1	601.6	0.50
11	0.45	180	360	FLY-ASH	40	486.6	ELECTRIC ARC FURNACE SLAG	25.6	613.1	601.6	0.0
12	0.45	180	360	LADLE FURNACE SLAG	40	461.3	GLASS POWDER	51.3	613.1	601.6	0.0
13	0.50	185	259	LADLE FURNACE SLAG	111	505.9	STEEL POWDER	26.6	607.8	593.9	0.0
14	0.50	185	333	FLY-ASH	37	452.6	STEEL POWDER	79.9	607.8	593.9	0.0
15	0.50	185	333	BLAST FURNACE SLAG	37	479.3	GLASS POWDER	53.3	607.8	593.9	0.0
16	0.50	185	296	LADLE FURNACE SLAG	74	505.9	GLASS POWDER	26.6	607.8	593.9	0.0
17	0.50	185	296	FLY-ASH	74	452.6	ELECTRIC ARC FURNACE SLAG	79.9	607.8	593.9	0.0
18	0.50	185	259	BLAST FURNACE SLAG	111	479.3	ELECTRIC ARC FURNACE SLAG	53.3	607.8	593.9	0.0

Table 3.18 Concrete Mix Design Proportion using specific gravity of by-product (Approach -2)

TRAIL NO.	WATER TO CEMENT RATIO	WATER (kg/m³)	BINDER (kg/m³)			FINE AGGREGATE (kg/m³)			COARSE AGGREGATE (kg/m³)		SUPER-PLASTICIZER (PERCHANTA- GE OF WEIGHT OF CEMENT)
			CEMENT	REPLACEMENT MATERIAL	AMOUNT	SAND	REPLACEMENT MATERIAL	AMOUNT	20 MM	10 MM	
1	0.40	170	382.2	BLAST FURNACE SLAG	40.1	391.9	GLASS POWDER	20.4	668.1	652.8	1.0
2	0.40	170	297.3	FLY-ASH	82.2	371.3	GLASS POWDER	40.7	668.1	652.8	1.5
3	0.40	170	339.7	FLY-ASH	54.8	371.3	ELECTRIC ARC FURNACE SLAG	54.8	668.1	652.8	1.0
4	0.40	170	382.2	LADLE FURNACE SLAG	34.3	350.6	ELECTRIC ARC FURNACE SLAG	34.3	668.1	652.8	1.0
5	0.40	170	297.3	LADLE FURNACE SLAG	102.8	350.6	STEEL POWDER	74.3	668.1	652.8	1.5
6	0.40	170	339.7	BLAST FURNACE SLAG	80.2	391.9	STEEL POWDER	24.8	668.1	652.8	1.0
7	0.45	180	319.9	LADLE FURNACE SLAG	51.6	461.3	STEEL POWDER	61.5	613.1	601.6	0.0
8	0.45	180	319.9	BLAST FURNACE SLAG	75.5	435.6	ELECTRIC ARC FURNACE SLAG	103.6	613.1	601.6	0.0
9	0.45	180	279.9	BLAST FURNACE SLAG	113.2	435.6	GLASS POWDER	75.9	613.1	601.6	0.75
10	0.45	180	279.9	FLY-ASH	77.4	486.8	STEEL POWDER	30.8	613.1	601.6	0.50
11	0.45	180	359.9	FLY-ASH	25.8	486.6	ELECTRIC ARC FURNACE SLAG	34.5	613.1	601.6	0.0
12	0.45	180	359.9	LADLE FURNACE SLAG	32.3	461.3	GLASS POWDER	50.6	613.1	601.6	0.0
13	0.50	185	258.2	LADLE FURNACE SLAG	89.3	505.9	STEEL POWDER	35.9	607.8	593.9	0.0
14	0.50	185	332	FLY-ASH	23.8	452.6	STEEL POWDER	95.9	607.8	593.9	0.0
15	0.50	185	332	BLAST FURNACE SLAG	34.8	479.3	GLASS POWDER	63.9	607.8	593.9	0.0
16	0.50	185	295.1	LADLE FURNACE SLAG	59.5	505.9	GLASS POWDER	26.3	607.8	593.9	0.0
17	0.50	185	295.1	FLY-ASH	47.6	452.6	ELECTRIC ARC FURNACE SLAG	78.8	607.8	593.9	0.0
18	0.50	185	258.2	BLAST FURNACE SLAG	104.5	479.3	ELECTRIC ARC FURNACE SLAG	71.8	607.8	593.9	0.0

Figure 3.1 Flow chart of Taguchi method

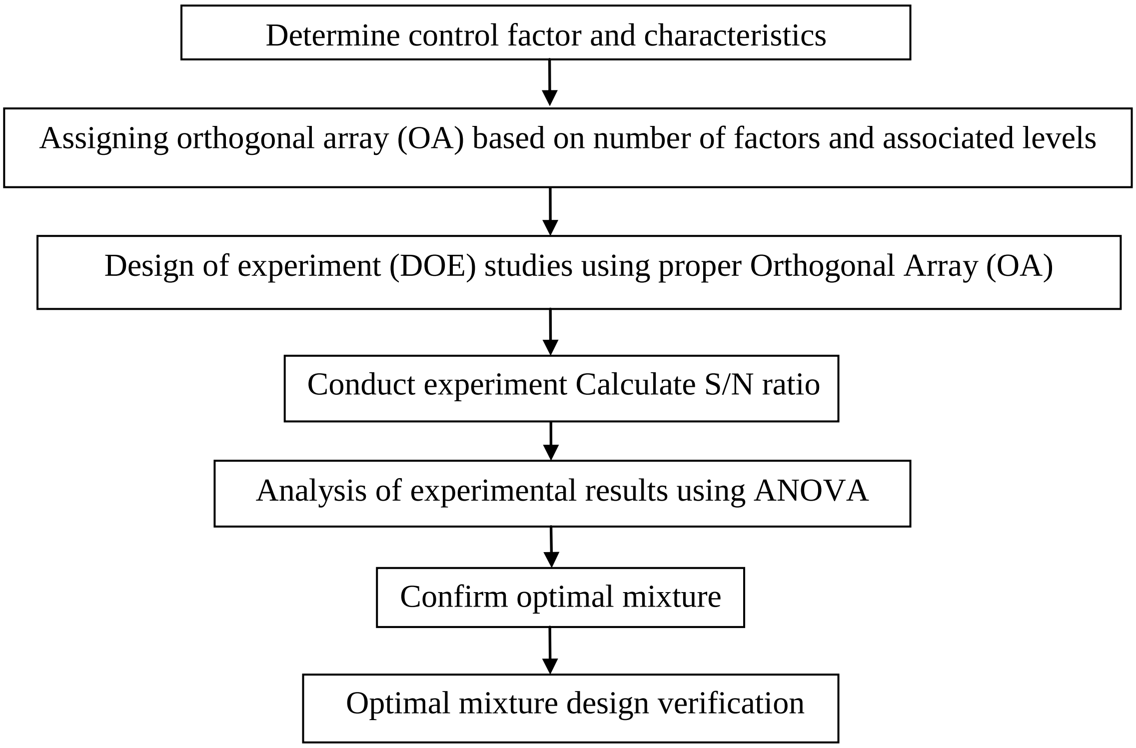


Figure 3.2 Automatic compressions testing machine (courtesy: Structure lab TU, Patiala)

Figure 3.3 Universal testing machines (courtesy: Structure lab TU, Patiala)

Figure 3.4 Water permeability testing machine (courtesy: Structure lab TU, Patiala)

a) Test apparatus **b) Specimen container** **c) Air compressor**

a) Pozzolanic Portland cement (Fly-ash based) **b) Fine aggregate (Sand)** **c) Conplast SP 43**

d) Coarse aggregate (20 mm) **e) Coarse aggregate (10 mm)**

Figure 3.5 Material

a) Blast furnace slag **b) Ladle furnace slag** **c) Fly-ash**

Figure 3.6 By-product used as binder replacement

a) Electric arc furnace slag (b) Glass powder (c) Steel powder (d) steel scrap

Figure 3.7 By-product used as fine aggregate replacement

a) Loosen of mould b) Cleaning of mould c) Bolting of mould

d) Tighten of mould e) Oiling of mould f) Pouring of mix

g) Vibrated the mix in vibrated table h) Casted cubes

Figure 3.8 Casting of specimens

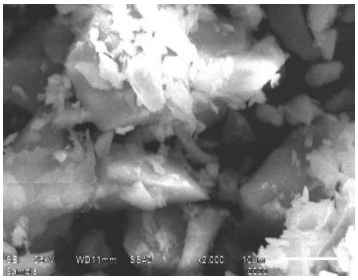
a) Opening of bolted mould **b) Curing of concrete in water tank**

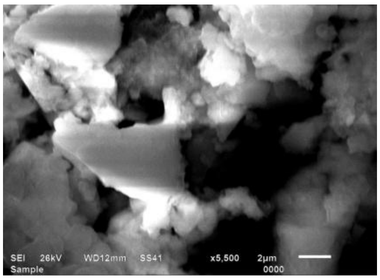
Figure 3.9 Curing of specimens

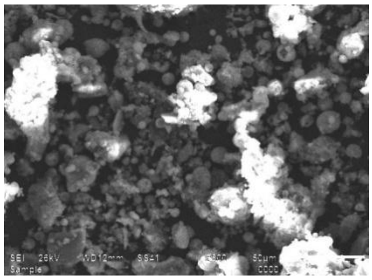
Figure 3.10 Compressive strength measurements (ACTM) (Structure lab TU, Patiala)

Figure 3.11 Splitting tensile strength measurements (UTM) (Structure lab TU, Patiala)

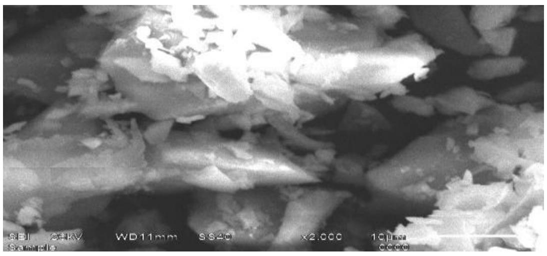
Figure 3.12 Depth of water penetration measurements (WPTM) (from Structure lab TU, Patiala)

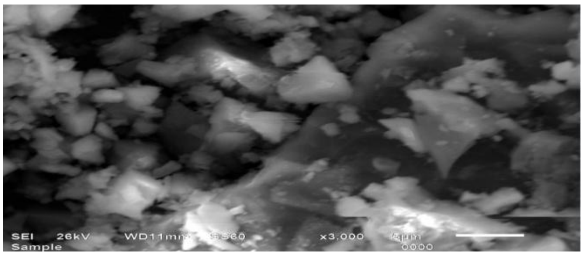






a) Blast Furnace Slag **b) Ladle Furnace Slag** **c) Fly-Ash**





d) Glass Powder **e) Electric Arc Furnace Slag**

Figure 3.13 SEM micrography of by-products

4.0 GENERAL

The proportioning of mixes for various replacements by the industrial by-products, as per the L18 design, was carried out using two different approaches. The first approach involved a direct partial percentage replacement in the quantities calculated for the design mix, wherein the quantities of material are calculated without considering the effect of variable specific gravities of the original material and its replacement.

The effect of various parameters such as water to cement ratio, by-product percentage used as a binder, by-product percentage used as a fine-aggregate, type of by-product used as a binder, type of by-product used as a fine-aggregate and curing time were evaluated using ANOVA and factorial design analysis. A confidence interval of 95% has been used for the analysis. 18 trials were conducted in the experiment using L18 experimental design. Two repetitions for each of 18 trials were completed so as to measure Signal to Noise ratio(S/N ratio) separately using the above mentioned two approaches.

4.1 METHODOLOGY FOR EVALUATING THE PERFORMANCE OF DESIGN

The results were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The signal to noise ratio (S/N ratio) is an indication of the amount of variation present in the process. The S/N ratio has been calculated to identifying the major contributing factors that cause variation in compressive strength. The main effect plot is used to estimate the optimal design conditions. A separate analysis has also been carried out to study the effect of curing time on other parameters for compressive strength, splitting tensile strength and water permeability.

Compressive strength and splitting tensile strength are a “Higher the Better” type response and are given by a logarithmic function based on the mean square division [51].

$$S/N = -10 * \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right) \quad \ldots\ldots (4.1)$$

Where $\log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{Y_i^2}\right)$ = Mean square deviation for higher the better response

4.1.1 Analysis of Variance using Approach-1

Analysis of Variance - Compressive Strength

The results of compressive strength for each of the 18 trials with repetitions are given in Table 4.1. The results were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean compressive strength at 95% confidence interval is given in Table 4.2. The Variation data for each factor were F-tested to find significance of each. The principal of the F-test is that the larger the F values for a particular parameter, the greater the effect on the performance characteristics due to the change in the process parameter.

ANOVA table shows that curing time (F value 93.138) is the factor that significantly affects the compressive strength followed by type of by-product used as a binder (F value 7.786) and water to cement ratio (F value 5.929). All other factors namely by-product percentage used as a binder, by-product percentage used as a fine-aggregate and type of by-product used as a fine-aggregate were found to be insignificant. Table 4.3 shows the rank of various factors in the term of their relative significance. Curing time has the highest rank signifying higher contribution to compressive strength and by-product percentage used as a binder has the lowest rank and was observed to be insignificant in affecting compressive strength. Main effect plot for the mean compressive strength is shown in Figure 4.1 which shows the variation of compressive strength with the input parameters.

Analysis of Variance - Splitting Tensile Strength

The results of splitting tensile strength for each of the 18 trials with repetitions are given in Table 4.12. ANOVA Table 4.13 shows that curing time (F value 489.59) is the factor that significantly affects the splitting tensile strength followed by type of by-product used as a binder (F value 39.091), by-product percentage used as a Binder (F value 7.281) and water to cement ratio (F value 5.904). All other factors namely by-product percentage used as a fine-aggregate and type of by-product used as a fine-aggregate were found to be insignificant. Table 4.14 shows the rank of various factors in the term of their relative significance. Curing time has the highest rank signifying higher contribution to splitting tensile strength and by-product percentage used as a fine-aggregate has the lowest rank and was observed to be insignificant in affecting splitting tensile strength. Main effect plot for the mean splitting tensile strength is shown in Figure 4.6 which shows the variation of splitting tensile strength with the input parameters.

Analysis of Variance - Water Penetration Depth

The results of water penetration depth for each of the 18 trials with repetitions are given in Table 4.23. ANOVA Table 4.24 shows that curing time (F value 57.022) is the factor that significantly affects the water penetration depth followed by by-product percentage used as a Binder (F value 8.235), type of by-product used as a fine aggregate (F value 6.734) and type of by-product used as a binder (F value 6.350). All other factors namely by-product percentage used as a fine-aggregate and water to cement ratio were found to be insignificant. Table 4.25 shows the rank of various factors in the term of their relative significance. Curing time has the highest rank signifying higher contribution to water penetration depth and by-product percentage used as a fine-aggregate has the lowest rank and was observed to be insignificant in affecting water penetration depth. Main effect plot for the mean water penetration depth is shown in Figure 4.11 which shows the variation of water penetration depth with the input parameters.

4.1.2 Optimal Design consideration

Compressive Strength

In this experimental analysis, the main effect plot in Figure 4.1 is used to estimate the mean compressive strength with optimal design conditions. In Table 4.6 it is concluded that highest compressive strength was achieve when water to cement ratio 0.40, ground granulated blast furnace slag as a binder and curing time 56 days were selected. In S/N ratio highest compressive strength was found when water to cement-0.40, ground granulated blast furnace slag(GGBFS) as a binder, glass powder as a fine aggregate and curing time 56 days were selected. In Some case, the same levels of the significant factors provide the higher average and reduced variability; hence nothing has to be compromised. In Some case, the level of factors which improve the average and improve the uniformity may conflict which means compromise may have to be reached. Moreover, a compromise may have to occur when multiple responses are considered and the same level factors may cause one response to improve and another to reduce.

Estimating the mean

Compressive Strength is a "Higher the better" type response. In this experimental analysis different experimental trials have been chosen to obtain satisfactory results. After conducting the experiments the optimum treatment condition with in the experiments determined on the basis of prescribed combination of factor levels is determined to one of those in the experiment.

Mean value of Compressive Strength is given by:

$\mu_{A1, D1, F3} = \overline{A_1} + \overline{D_1} + \overline{F_3} - 2\overline{T}$

$= 34.413+35.308+43.388 -2(574.9/18)$

$= 113.109 – 63.877$

$= 49.23\ N/mm^2$

Confidence Interval around the Estimating mean

The Confidence interval signifies the maximum and minimum value between which the true average fall at some stated percentage of confidence. The estimate of the mean μ is only a point estimate based on the averages of results obtained from the experiment. Statistically it specify that there is 50% chance of the true averages being greater than μ and a 50% chance of the true average being less than μ.

Confidence Interval around the estimated Compressive Strength

$$CI = \sqrt[2]{\frac{F_{\alpha,v1,v2}\, V_e}{n_{eff}}} \quad \text{Where } F_{\alpha,v1,v2} = \text{F ratio}$$

α = risk (0.05)

Confidence = 1-α

ν_1 = degree of freedom for mean which is always = 1

ν_2 = degree of freedom for error = ν_e = 5

$$n_{eff} = \frac{N}{1+dof_{A1,D1,F3}} = \frac{18}{1+(2+2+2)} = 2.57$$

Where N = number of trials in the experiment

$$CI = \sqrt[2]{\frac{F_{\alpha,v1,v2} V_e}{n_{eff}}}$$

$$= \sqrt[2]{\frac{6.61*6.778}{2.57}}$$

$$= \pm 4.175 \text{ N/mm}^2$$

Thus the confidence interval around the estimated mean of compressive Strength is given by 49.231 ± 4.175 N/mm^2.

Splitting Tensile Strength

In this experimental analysis, the main effect plot in Figure 4.6 is used to estimate the mean splitting tensile strength with optimal design conditions. In Table 4.17 it is concluded that highest splitting tensile strength was achieve when water to cement ratio 0.40, 20 % ground granulated blast furnace slag as a binder and curing time 56 days were selected. In S/N ratio highest splitting tensile strength was found when water to cement ratio 0.40, 20 % ground granulated blast furnace slag as a binder, glass powder as a fine aggregate and curing time 56 days were selected.

Estimating the mean

Mean value of Splitting Tensile Strength is given by:

$$\mu_{A1, B2, D1, F3} = \overline{A_1} + \overline{B_2} + \overline{D_1} + \overline{F_3} - 3\overline{T}$$

$$= 2.806+2.803+2.963 + 3.651 -3(48.41/18)$$

$$= 12.223 – 8.068$$

$$= 4.155 \text{ N/mm}^2$$

Confidence Interval around the Estimating mean

$$n_{eff} = \frac{N}{1+dof_{A1,D1,F3}} = \frac{18}{1+(2+2+2+2)} = 2.0$$

Where N = number of trials in the experiment

$$CI = \sqrt[2]{\frac{6.61*0.072}{2.0}}$$

$= \pm 0.487\ N/mm^2$

Thus the confidence interval around the estimated mean of splitting tensile strength is given by $4.155 \pm 0.487\ N/mm^2$.

Water Penetration Depth

In this experimental analysis, the main effect plot in Figure 4.11 is used to estimate the mean water penetration depth with optimal design conditions. In Table 4.26 it is concluded that lowest water penetration depth was achieve when 10 % ground granulated blast furnace slag as a binder, electric arc furnace slag as a fine aggregate and curing time 56 days were selected. Water penetration depth is a "Lower the better" type response.

Estimating the mean

Mean value of water penetration depth is given by:

$$\mu_{B1,\ D1,\ E2,\ F3} = \overline{B_1} + \overline{D_1} + \overline{E_2} + \overline{F_3} - 3\overline{T}$$

$= 29.166+24.667+28.833 + 16.166 -3(605/18)$

$= 98.832 - 33.611$

$= 65.220$ mm

Confidence Interval around the Estimating mean

$$n_{eff} = \frac{N}{1+dof_{A1,\ D1,\ F3}} = \frac{18}{1+(2+2+2+2)} = 2.0$$

Where N = number of trials in the experiment

$$CI = \sqrt[2]{\frac{6.61*60.424}{2.0}}$$

$= \pm 14.13$ mm

Thus the confidence interval around the estimated mean of Water penetration depth is given by 65.220 ± 14.13 mm.

4.1.3 Signal to noise ratio (S/N ratio)

Result for S/N ratio - Compressive Strength

Table 4.4 shows the ANOVA results for S/N ratio of compressive strength at 95% confident interval. Water to cement ratio, type of by-product used as a binder, type of by-product used as a fine aggregate and curing time are found to significant. According to F-test curing time (F value 243.94) was found to be most significant factor affecting the compressive strength followed by type of by-product used as a binder (F value 21.393), water to cement ratio (F value 20.570) and type of by-product used as a fine aggregate (F value 5.820). Main effect plot of S/N ratio for compressive strength are shown in Figure 4.2.Table 4.5 shows the ranks of various factors in the terms of their relative significance. Curing time has the highest rank which signifies that it provides highest contribution to compressive strength and by-product percentage used as a fine aggregate has the lowest rank and was found to be insignificant in affecting compressive strength.

Result for S/N ratio - Splitting Tensile Strength

Table 4.15 shows the ANOVA results for S/N ratio of splitting tensile strength. Water to cement ratio, type of by-product used as a binder, type of by-product used as a fine aggregate, by-product percentage used as a binder and curing time was observed to be most significant factors affecting the splitting tensile strength. According to F-test curing time (F value 485.61) was found to be most significant factor affecting the splitting tensile strength followed by type of by-product used as a binder (F value 41.946), water to cement ratio (F value 14.927), by-product percentage used as a binder (F value 10.771) and type of by-product used as a fine aggregate (F value 6.938). Main effect plot of S/N ratio for splitting tensile strength are shown in Figure 4.7. Table 4.16 shows the ranks of various factors in the terms of their relative significance. Curing time has the highest rank which signifies that it provides highest contribution to splitting tensile strength and by-product percentage used as a fine aggregate has the lowest rank and was found to be insignificant in affecting splitting tensile strength.

4.1.4 Effect of Curing Time

Effect of Curing Time on Compressive Strength

A separate analysis has also been carried out to study the effect of curing time on other parameters for Compressive strength. For the same the data has been split into three parts; 7 days, 28 days and 56 days. Results for compressive strength after 7 days, 28 days and 56 days of curing are shown in Table 4.7. The Response table for means of compressive strength using the results of Table 4.7 for 7 days, 28 days and 56 days was calculated and shown in Table 4.8, 4.9 and 4.10 respectively. Finally the significant factors for compressive strength for each part i.e. 7 days, 28 days and 56 days have been given in Table 4.11.

Optimal Design considering Effect of Curing Time

In this experimental analysis, the main effect in Figure 4.3, 4.4 and 4.5 are used to estimate the mean compressive strength with optimal design condition for 7days, 28 days and 56 days of curing time respectively. In Table 4.11 it is concluded that highest compressive strength was achieved for 7 days when water to cement ratio 0.40, 20% granulated blast furnace slag as a binder and glass powder as a fine aggregate were selected. The highest compressive strength was achieved for 28 days when water to cement ratio 0.40, 30% ladle furnace slag as a binder and 10% glass powder as a fine aggregate were selected. For 56 days the highest compressive strength was achieved when water to cement ratio 0.40, 30% fly-ash as a binder and 15% glass powder as a fine aggregate were selected.

Effect of Curing Time on Splitting Tensile Strength

Results for splitting tensile strength after 7 days, 28 days and 56 days of curing are shown in Table 4.18. The Response table for means of splitting tensile strength using the results of Table 4.18 for 7 days, 28 days and 56 days has been calculated and shown in Table 4.19, 4.20 and 4.21 respectively. Finally the significant factors for splitting tensile strength for each part i.e. 7 days, 28 days and 56 days have been given in Table 4.22.

Optimal Design considering Effect of Curing Time

In this experimental analysis, the main effect in Figure 4.8, 4.9 and 4.10 are used to estimate the mean splitting tensile strength with optimal design condition for 7days, 28 days and 56 days of curing time respectively. In Table 4.22 it is concluded that highest splitting tensile strength was achieved for 7 days when water to cement ratio 0.40, 10% granulated blast furnace slag as a binder and glass powder is used as a fine aggregate were selected. The highest splitting tensile strength was achieved for 28 days when water to cement ratio 0.40, 20% ladle furnace slag as a binder and 5% glass powder is used as a fine aggregate were selected. For 56 days the highest splitting tensile strength was achieved when water to cement ratio 0.40, 30% fly-ash as a binder and 10% by-product is used as a fine aggregate were selected.

Effect of Curing Time on Water Penetration Depth

Results for water penetration depth after 7 days, 28 days and 56 days of curing are shown in Table 4.27. The Response table for means of water penetration depth using the results of Table 4.27 for 7 days, 28 days and 56 days has been calculated and shown in Table 4.28, Table 4.29 and Table 4.30 respectively. Finally the significant factors for water penetration depth for each part i.e. 7 days, 28 days and 56 days have been given in Table 4.31.

Optimal Design considering Effect of Curing Time

In this experimental analysis, the main effect in Figure 4.12, 4.13 and 4.14 are used to estimate the mean water penetration depth with optimal design condition for 7days, 28 days and 56 days of curing time respectively. In Table 4.31 it is concluded that lowest water penetration depth was achieved for 7 days when water to cement ratio 0.40, 10% Granulated blast furnace slag as a binder and 5% Glass powder is used as a fine aggregate were selected. The lowest water penetration depth was achieved for 28 days when water to cement ratio 0.40, 30% Ladle furnace slag as a binder and 5% Glass powder is used as a fine aggregate were selected. For 56 days the lowest water penetration depth was achieved when water to cement ratio 0.40, 20% Ladle furnace slag is used as a binder and 15% Electric arc furnace slag as a fine aggregate were selected.

Table 4.1 Results for Compressive Strength (Approach -1)

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Compressive Strength			Mean	S/N Ratio
							I	II	III		
1	0.40	10%	5	GGBFS	Glass Powder	7	26.65	27.10	27.20	26.99	28.62
2	0.40	20%	10	FLY-ASH	EAFS	28	32.59	31.04	31.56	31.73	30.02
3	0.40	30%	15	LFS	Steel Powder	56	40.73	40.92	40.68	40.78	32.2
4	0.45	10%	5	FLY-ASH	EAFS	56	39.47	39.45	39.48	39.44	31.92
5	0.45	20%	10	LFS	Steel Powder	7	21.35	20.46	22.20	21.34	26.57
6	0.45	30%	15	GGBFS	Glass Power	28	35.52	36.61	37.92	36.68	31.30
7	0.50	10%	10	GGBFS	Steel Powder	28	28.40	28.21	28.25	28.30	29.03
8	0.50	20%	15	FLY-ASH	Glass Power	56	39.84	38.47	38.58	38.84	31.78
9	0.50	30%	5	LFS	EAFS	7	16.91	16.80	16.45	16.72	24.50
10	0.40	10%	15	LFS	EAFS	28	36.12	36.18	37.16	36.49	31.24
11	0.40	20%	5	GGBFS	Steel Powder	56	49.82	49.77	49.33	49.64	33.92
12	0.40	30%	10	FLY-ASH	Glass Power	7	21.27	20.55	20.72	20.85	26.40
13	0.45	10%	10	LFS	Glass Power	56	46.40	46.33	46.48	46.50	33.34
14	0.45	20%	15	GGBFS	EAFS	7	23.82	26.08	25.42	25.11	27.97
15	0.45	30%	5	FLY-ASH	Steel Powder	28	26.51	25.13	25.88	25.84	28.24
16	0.50	10%	15	FLY-ASH	Steel Powder	7	16.87	17.3	16.92	17.02	24.61
17	0.50	20%	5	LFS	Glass Power	28	27.84	27.54	27.13	27.50	28.80
18	0.50	30%	10	GGBFS	EAFS	56	46.08	44.71	44.13	45.13	33.10

Table 4.2 ANOVA for means of Compressive Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio(A)	93.269	2	46.634	5.929	5.79	79.713	5.313
By-product as a Binder used (Percent) (B)	7.961	2	3.980	0.506	5.79		0.453
By-product as a Fine Aggregate used (Percent) (C)	7.667	2	3.833	0.487	5.79		0.436
By-product used as a Binder(D)	122.48	2	61.242	7.786	5.79	108.92	6.979
By-product used as a Fine Aggregate(E)	19.606	2	9.803	1.246	5.79		1.116
Curing Time (Days) (F)	1465.09	2	732.5	93.138	5.79	1451.5	83.46
Error	39.325	5	7.865				2.240
Total	1755.40	17					100
e pooled	74.56	11	6.778			115.27	4.245

Table 4.3 Response table for means of Compressive Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	34.413	32.456	31.011	35.308	32.893	21.338
2	32.485	32.36	32.308	28.953	32.436	31.09
3	28.918	31	32.486	31.555	30.486	43.388
Delta	5.495	1.456	1.465	6.355	2.406	22.05
Rank	3	6	5	2	4	1

Table 4.4 ANOVA for S/N Ratio of Compressive Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio(A)	9.963	2	4.981	20.570	5.79	9.225	6.889
By-product as a Binder used (Percent) (B)	1.187	2	0.593	2.451	5.79		0.821
By-product as a Fine Aggregate used (Percent) (C)	0.924	2	0.462	1.908	5.79		0.639
By-product used as a Binder(D)	10.362	2	5.181	21.393	5.79	9.624	7.165
By-product used as a Fine Aggregate(E)	2.819	2	1.409	5.820	5.79	2.081	1.949
Curing Time (Days) (F)	118.16	2	59.08	243.94	5.79	117.4 22	81.698
Error	1.210	5	0.242				0.837
Total	144..63	17					100
e pooled	3.321	9	0.369				2.297

Table 4.5 Response table for S/N Ratio of Compressive Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	30.398	29.975	29.323	30.651	30.032	26.437
2	29.887	29.842	29.738	28.826	29.784	29.767
3	28.627	29.275	29.851	29.434	29.096	32.709
Delta	1.770	0.567	0.527	1.825	0.935	6.271
Rank	3	5	6	2	4	1

Table 4.6 Significant factors for Compressive Strength

Factors	Affecting mean		Affecting variation (S/N ratio)	
	Contribution	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 1- 0.40	Significant	Level 1- 0.40
By-product as a Binder used (Percent)	Insignificant	-	Insignificant	-
By-product as a Fine aggregate used (Percent)	Insignificant	-	Insignificant	-
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 1- GGBFS
By-product used as a Fine Aggregate	Insignificant	-	Significant	Level 1- Glass Powder
Curing Time (Days)	Significant	Level 3- 56 Days	Significant	Level 3- 56 Days

Table 4.7 Results for Compressive Strength according to curing time

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Compressive Strength			Mean	S/N Ratio
							I	II	III		
1	0.40	10%	5	GGBFS	Glass Powder	7 DAYS	26.65	27.10	27.20	26.99	28.62
2	0.45	20%	10	LFS	Steel Powder		21.35	20.46	22.20	21.34	26.57
3	0.50	30%	5	LFS	EAFS		16.91	16.80	16.45	16.72	24.50
4	0.40	30%	10	FLY-ASH	Glass Power		21.27	20.55	20.72	20.85	26.40
5	0.45	20%	15	GGBFS	EAFS		23.82	26.08	25.42	25.11	27.97
6	0.50	10%	15	FLY-ASH	Steel Powder		16.87	17.3	16.92	17.02	24.61
1	0.40	20%	10	FLY-ASH	EAFS	28 DAYS	32.59	31.04	31.56	31.73	30.02
2	0.45	30%	15	GGBFS	Glass Power		35.52	36.61	37.92	36.68	31.30
3	0.50	10%	10	GGBFS	Steel Powder		28.40	28.21	28.25	28.30	29.03
4	0.40	10%	15	LFS	EAFS		36.12	36.18	37.16	36.49	31.24
5	0.45	30%	5	FLY-ASH	Steel Powder		26.51	25.13	25.88	25.84	28.24
6	0.50	20%	5	LFS	Glass Power		27.84	27.54	27.13	27.50	28.80
1	0.40	30%	15	LFS	Steel Powder	56 DAYS	40.73	40.92	40.68	40.78	32.2
2	0.45	10%	5	FLY-ASH	EAFS		39.47	39.45	39.48	39.44	31.92
3	0.50	20%	15	FLY-ASH	Glass Power		39.84	38.47	38.58	38.84	31.78
4	0.40	20%	5	GGBFS	Steel Powder		49.82	49.77	49.33	49.64	33.92
5	0.45	10%	10	LFS	Glass Power		46.40	46.33	46.48	46.50	33.34
6	0.50	30%	10	GGBFS	EAFS		46.08	44.71	44.13	45.13	33.10

Table 4.8 Response table for means of Compressive Strength (7 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	23.92	22.005	21.855	26.05	23.92
2	23.225	23.225	21.095	19.03	20.915
3	16.87	18.785	21.065	18.935	19.18
Delta	7.05	4.44	0.79	7.115	4.74
Rank	2	4	5	1	5

Table 4.9 Response table for means of Compressive Strength (28 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	34.11	29.615	30.015	28.785	34.11
2	31.26	31.26	36.585	32.49	27.07
3	27.9	32.395	26.67	31.995	32.09
Delta	6.21	2.78	9.915	3.705	7.04
Rank	3	5	1	4	2

Table 4.10 Response table for means of Compressive Strength (56 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	45.21	42.985	39.81	43.64	45.21
2	42.97	42.97	44.54	39.14	42.67
3	41.985	44.24	45.815	47.385	42.285
Delta	3.225	1.285	6.005	8.245	2.925
Rank	3	5	2	1	4

Table 4.11 Significant factors for Compressive Strength

Factors	Affecting mean (7 Days)		Affecting mean (28 Days)		Affecting mean (56 Days)	
	Contribution	**Best Level**	**Contribution**	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 1- 0.40	Significant	Level 1- 0.40	Significant	Level 1- 0.40
By-product as a Binder used (Percent)	Significant	Level 2- 20 %	Significant	Level 3- 30 %	Significant	Level 3- 30 %
By-product as a Fine aggregate used (Percent)	Insignificant	-	Significant	Level 2- 10 %	Significant	Level 3- 15 %
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 2- LFS	Significant	Level 3- FLY-ASH
By-product used as a Fine Aggregate	Significant	Level 1- Glass Powder	Significant	Level 1- Glass Powder	Significant	Level 1- Glass Powder

Table 4.12 Results for Splitting Tensile Strength

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Splitting Tensile Strength		Mean	S/N Ratio
							I	II		
1	0.40	10%	5	GGBFS	Glass Powder	7	2.20	2.30	2.25	7.037
2	0.40	20%	10	FLY-ASH	EAFS	28	2.80	2.83	2.82	8.989
3	0.40	30%	15	LFS	Steel Powder	56	3.28	3.38	3.30	10.45
4	0.45	10%	5	FLY-ASH	EAFS	56	3.54	3.55	3.50	10.99
5	0.45	20%	10	LFS	Steel Powder	7	1.59	1.58	1.59	4.00
6	0.45	30%	15	GGBFS	Glass Power	28	2.89	3.02	2.95	9.404
7	0.50	10%	10	GGBFS	Steel Powder	28	2.76	2.77	2.77	8.833
8	0.50	20%	15	FLY-ASH	Glass Power	56	3.77	4.00	3.90	11.78
9	0.50	30%	5	LFS	EAFS	7	1.20	1.30	1.25	1.917
10	0.40	10%	15	LFS	EAFS	28	2.53	2.74	2.60	8.394
11	0.40	20%	5	GGBFS	Steel Powder	56	4.09	4.09	4.09	12.23
12	0.40	30%	10	FLY-ASH	Glass Power	7	1.73	1.80	1.78	4.929
13	0.45	10%	10	LFS	Glass Power	56	3.45	3.40	3.42	10.69
14	0.45	20%	15	GGBFS	EAFS	7	2.03	2.00	2.02	6.085
15	0.45	30%	5	FLY-ASH	Steel Powder	28	2.30	2.60	2.45	7.734
16	0.50	10%	15	FLY-ASH	Steel Powder	7	1.60	1.63	1.62	4.162
17	0.50	20%	5	LFS	Glass Power	28	2.36	2.42	2.40	7.565
18	0.50	30%	10	GGBFS	EAFS	56	3.36	3.70	3.70	10.93

Table 4.13 ANOVA for means of Splitting Tensile Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio (A)	0.131	2	0.065	5.904	5.79	0.013	1.075
By-product as a Binder used (Percent)(B)	0.161	2	0.080	7.281	5.79	0.017	1.326
By-product as a Fine Aggregate used (Percent) (C)	0.017	2	0.008	0.798	5.79		0.145
By-product used as a Binder(D)	0.865	2	0.432	39.091	5.79	0.721	7.123
By-product used as a Fine Aggregate(E)	0.079	2	0.039	3.603	5.79		0.656
Curing Time (Days) (F)	10.835	2	5.417	489.59	5.79	10.69	89.216
Error	0.553	5	0.011				0.455
Total	12.145	17				12.14	100
e pooled	0.649	9	0.072			0.704	1.26

Table 4.14 Response table for means of Splitting Tensile Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	2.806	2.693	2.656	2.963	2.783	1.751
2	2.655	2.803	2.68	2.678	2.648	2.665
3	2.606	2.571	2.731	2.426	2.636	3.651
Delta	0.2	0.231	0.075	0.536	0.146	1.9
Rank	5	3	6	2	4	1

Table 4.15 ANOVA for S/N Ratio of Splitting Tensile Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio (A)	3.920	2	1.960	14.927	5.79	3.54	2.640
By-product as a Binder used (Percent) (B)	2.829	2	1.414	10.771	5.79	2.449	1.905
By-product as a Fine Aggregate used (Percent) (C)	0.675	2	0.337	2.572	5.79		0.455
By-product used as a Binder(D)	11.031	2	5.515	41.996	5.79	10.65	7.428
By-product used as a Fine Aggregate(E)	1.822	2	0.911	6.938	5.79	1.442	1.227
Curing Time (Days) (F)	127.55	2	63.77	485.61	5.79	127.2	85.90
Error	0.656	5	0.131				0.442
Total	148.49	17				148.5	100
e pooled	1.331	7	0.190			3.219	0.897

Table 4.16 Response table for S/N Ratio of Splitting Tensile Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	8.6719	8.3522	7.9136	9.0867	8.5678	4.6886
2	8.1516	8.4419	8.0618	8.0974	7.884	8.4872
3	7.5302	7.5596	8.3782	7.1695	7.9019	11.178
Delta	1.1417	0.8823	0.4646	1.9172	0.6838	6.4892
Rank	3	4	6	2	5	1

Table 4.17 Significant factors for Splitting Tensile Strength

Factors	Affecting mean		Affecting variation (S/N ratio)	
	Contribution	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 1- 0.40	Significant	Level 1- 0.40
By-product as a Binder used (Percent)	Significant	Level 2-20 %	Significant	Level 2-20 %
By-product as a Fine aggregate used (Percent)	Insignificant	-	Insignificant	-
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 1- GGBFS
By-product used as a Fine Aggregate	Insignificant	-	Significant	Level 1- Glass Powder
Curing Time (Days)	Significant	Level 3- 56 Days	Significant	Level 3- 56 Days

Table 4.18 Results for Splitting Tensile Strength according to curing time

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Splitting Tensile Strength		Mean	S/N Ratio
							I	II		
1	0.40	10%	5	GGBFS	Glass Powder	7 DAYS	2.20	2.30	2.25	7.037
2	0.45	20%	10	LFS	Steel Powder		1.59	1.58	1.59	4.00
3	0.50	30%	5	LFS	EAFS		1.20	1.30	1.25	1.917
4	0.40	30%	10	FLY-ASH	Glass Power		1.73	1.80	1.78	4.929
5	0.45	20%	15	GGBFS	EAFS		2.03	2.00	2.02	6.085
6	0.50	10%	15	FLY-ASH	Steel Powder		1.60	1.63	1.62	4.162
1	0.40	20%	10	FLY-ASH	EAFS	28 DAYS	2.80	2.83	2.82	8.989
2	0.45	30%	15	GGBFS	Glass Power		2.89	3.02	2.95	9.404
3	0.50	10%	10	GGBFS	Steel Powder		2.76	2.77	2.77	8.833
4	0.40	10%	15	LFS	EAFS		2.53	2.74	2.60	8.394
5	0.45	30%	5	FLY-ASH	Steel Powder		2.30	2.60	2.45	7.734
6	0.50	20%	5	LFS	Glass Power		2.36	2.42	2.40	7.565
1	0.40	30%	15	LFS	Steel Powder	56 DAYS	3.28	3.38	3.30	10.45
2	0.45	10%	5	FLY-ASH	EAFS		3.54	3.55	3.50	10.99
3	0.50	20%	15	FLY-ASH	Glass Power		3.77	4.00	3.90	11.78
4	0.40	20%	5	GGBFS	Steel Powder		4.09	4.09	4.09	12.23
5	0.45	10%	10	LFS	Glass Power		3.45	3.40	3.42	10.69
6	0.50	30%	10	GGBFS	EAFS		3.36	3.70	3.70	10.93

Table 4.19 Response table for means of Splitting Tensile Strength (7 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	2.015	1.935	1.75	2.135	2.015
2	1.805	1.805	1.685	1.42	1.635
3	1.435	1.515	1.82	1.7	1.605
Delta	0.58	0.42	0.135	0.715	0.41
Rank	2	3	5	1	4

Table 4.20 Response table for means of Splitting Tensile Strength (28 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	2.71	2.61	2.795	2.635	2.71
2	2.7	2.7	2.775	2.86	2.61
3	2.585	2.685	2.425	2.5	2.675
Delta	0.125	0.09	0.37	0.36	0.1
Rank	3	5	1	2	4

Table 4.21 Response table for means of Splitting Tensile Strength (56 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	3.695	3.5	3.6	3.36	3.695
2	3.46	3.46	3.795	3.7	3.66
3	3.8	3.995	3.56	3.895	3.6
Delta	0.34	0.535	0.235	0.535	0.095
Rank	3	2	4	1	5

Table 4.22 Significant factors for Splitting Tensile Strength

Factors	**Affecting mean (7 Days)**		**Affecting mean (28 Days)**		**Affecting mean (56 Days)**	
	Contribution	**Best Level**	**Contribution**	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 1- 0.40	Significant	Level 1- 0.40	Significant	Level 1- 0.40
By-product as a Binder used (Percent)	Significant	Level 1- 10 %	Significant	Level 2- 20 %	Significant	Level 3- 30 %
By-product as a Fine aggregate used (Percent)	Insignificant	-	Significant	Level 1- 5 %	Significant	Level 2- 10 %
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 2- LFS	Significant	Level 3- FLY-ASH
By-product used as a Fine Aggregate	Significant	Level 1- Glass Powder	Significant	Level 1- Glass Powder	Insignificant	-

Table 4.23 Results for Water Penetration Depth

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Water Penetration Depth
1	0.40	10%	5	GGBFS	Glass Powder	7	35
2	0.40	20%	10	FLY-ASH	EAFS	28	18
3	0.40	30%	15	LFS	Steel Powder	56	32
4	0.45	10%	5	FLY-ASH	EAFS	56	12
5	0.45	20%	10	LFS	Steel Powder	7	75
6	0.45	30%	15	GGBFS	Glass Power	28	25
7	0.50	10%	10	GGBFS	Steel Powder	28	16
8	0.50	20%	15	FLY-ASH	Glass Power	56	10
9	0.50	30%	5	LFS	EAFS	7	72
10	0.40	10%	15	LFS	EAFS	28	12
11	0.40	20%	5	GGBFS	Steel Powder	56	13
12	0.40	30%	10	FLY-ASH	Glass Power	7	65
13	0.45	10%	10	LFS	Glass Power	56	8
14	0.45	20%	15	GGBFS	EAFS	7	37
15	0.45	30%	5	FLY-ASH	Steel Powder	28	45
16	0.50	10%	15	FLY-ASH	Steel Powder	7	76
17	0.50	20%	5	LFS	Glass Power	28	32
18	0.50	30%	10	GGBFS	EAFS	56	22

Table 4.24 ANOVA for Water Penetration Depth

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio	234.11	2	117.05	2.058	5.79		2.476
By-product as a Binder used (Percent)	936.44	2	468.22	8.235	5.79	815.59	9.907
By-product as a Fine Aggregate used (Percent)	25.44	2	12.72	0.223	5.79		0.269
By-product used as a Binder	722.11	2	361.05	6.350	5.79	601.26	7.639
By-product used as a Fine Aggregate	765.77	2	382.88	6.734	5.79	644.92	8.101
Curing Time (Days)	6484.11	2	3242.05	57.022	5.79	6363.3	68.598
Error	284.27	5	56.85				3.007
Total	9452.27	17					100
e pooled	543.82	9	60.424			1027.2	5.752

Table 4.25 Response table for Water Penetration Depth

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	29.166	26.5	34.833	24.667	29.166	60
2	33.660	30.833	34	37.666	28.833	24.666
3	38	43.5	32	38.5	42.833	16.166
Delta	8.833	17	2.833	13.833	14	43.833
Rank	5	3	6	2	4	1

Table 4.26 Significant factors for Water Penetration Depth

Factors	Affecting mean	
	Contribution	**Best Level**
Water to Cement ratio	Insignificant	-
By-product as a Binder used (Percent)	Significant	Level 1-10 %
By-product as a Fine aggregate used (Percent)	Insignificant	-
By-product used as a Binder	Significant	Level 1-GGBFS
By-product used as a Fine Aggregate	Significant	Level 2-EAFS
Curing Time (Days)	Significant	Level 3- 56 Days

Table 4.27 Results for Water Penetration Depth

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Water Penetration Depth
1	0.40	10%	5	GGBFS	Glass Powder	7 DAYS	35
2	0.45	20%	10	LFS	Steel Powder		75
3	0.50	30%	5	LFS	EAFS		72
4	0.40	30%	10	FLY-ASH	Glass Power		65
5	0.45	20%	15	GGBFS	EAFS		37
6	0.50	10%	15	FLY-ASH	Steel Powder		76
1	0.40	20%	10	FLY-ASH	EAFS	28 DAYS	18
2	0.45	30%	15	GGBFS	Glass Power		25
3	0.50	10%	10	GGBFS	Steel Powder		16
4	0.40	10%	15	LFS	EAFS		12
5	0.45	30%	5	FLY-ASH	Steel Powder		45
6	0.50	20%	5	LFS	Glass Power		32
1	0.40	30%	15	LFS	Steel Powder	56 DAYS	32
2	0.45	10%	5	FLY-ASH	EAFS		12
3	0.50	20%	15	FLY-ASH	Glass Power		10
4	0.40	20%	5	GGBFS	Steel Powder		13
5	0.45	10%	10	LFS	Glass Power		8
6	0.50	30%	10	GGBFS	EAFS		22

Table 4.28 Response table for means of Water Penetration Depth (7 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	50	55.5	53.5	36	50
2	56	56	70	73.5	54.5
3	74	68.5	56.5	70.5	75.5
Delta	24	13	16.5	37.5	25.5
Rank	3	5	4	1	2

Table 4.29 Response table for means of Water Penetration Depth (28 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	15	25	17	31.5	15
2	35	35	18.5	20.5	30.5
3	24	14	38.5	22	28.5
Delta	20	21	21.5	11	15.5
Rank	2	1	4	5	3

Table 4.30 Response table for means of Water Penetration Depth (56 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	22.5	27	21	20	22.5
2	10	10	12.5	11	9
3	16	11.5	15	17.5	17
Delta	12.5	17	8.5	9	13.5
Rank	2	3	5	4	1

Table 4.31 Significant factors for Water Penetration Depth

Factors	Affecting mean (7 Days)		Affecting mean (28 Days)		Affecting mean (56 Days)	
	Contribution	**Best Level**	**Contribution**	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 1- 0.40	Significant	Level 1- 0.40	Significant	Level 2- 0.45
By-product as a Binder used (Percent)	Significant	Level 1- 10 %	Significant	Level 3- 30 %	Significant	Level 2- 20 %
By-product as a Fine aggregate used (Percent)	Significant	Level 1- 5 %	Significant	Level 1- 5 %	Significant	Level 3- 15 %
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 2- LFS	Significant	Level 2- LFS
By-product used as a Fine Aggregate	Significant	Level 1- Glass Powder	Significant	Level 1- Glass Powder	Significant	Level 2- Electric Arc Furnace Slag

Main effects plot for means

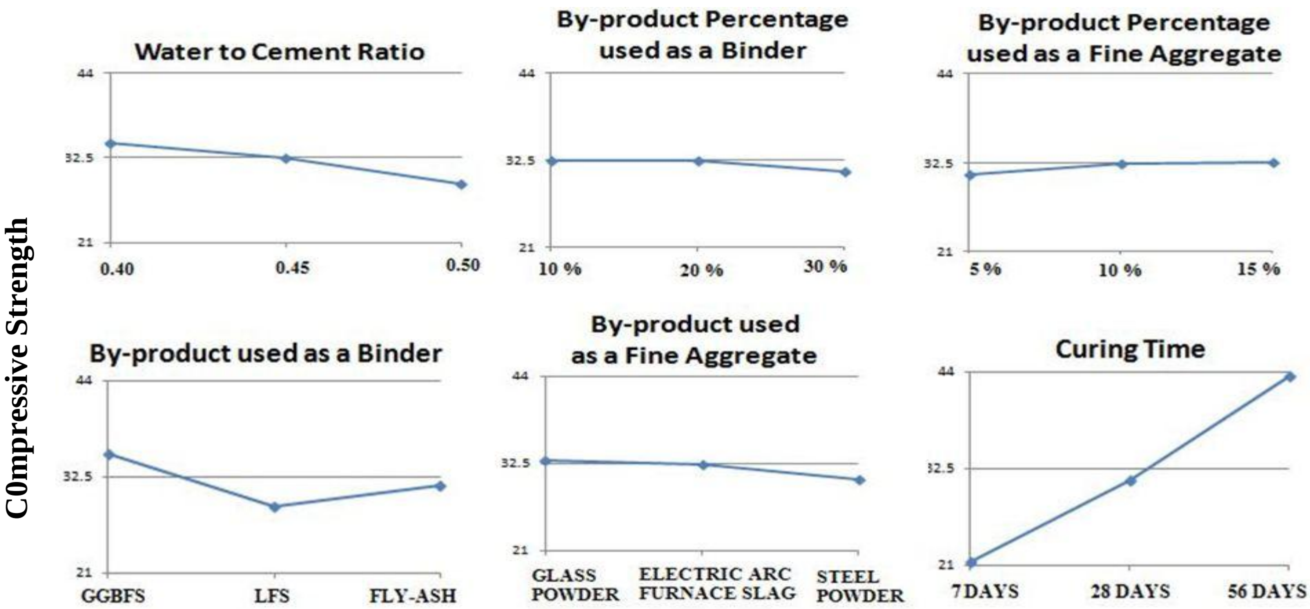
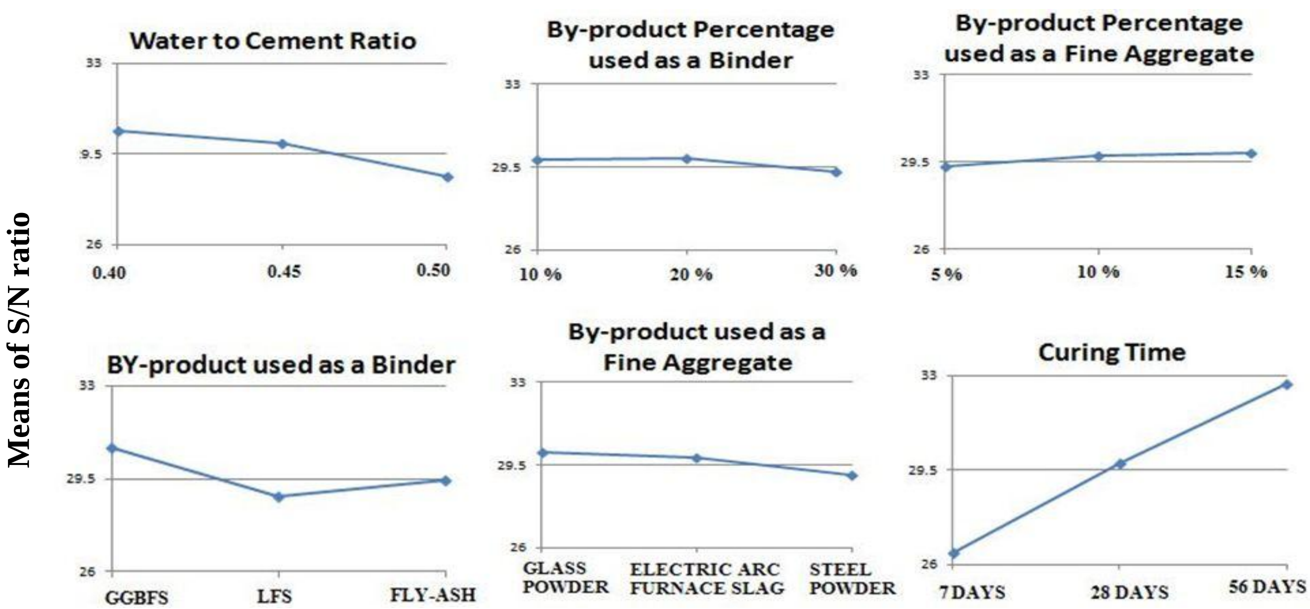


Figure 4.1: Main effects plot for Mean Compressive Strength (Approach -1)

Main effects plot for S/N ratio



S/N ratio = Higher the better

Figure 4.2: Main effects plot for S/N Ratio of Compressive Strength

Main effects plot for means (7 Days)

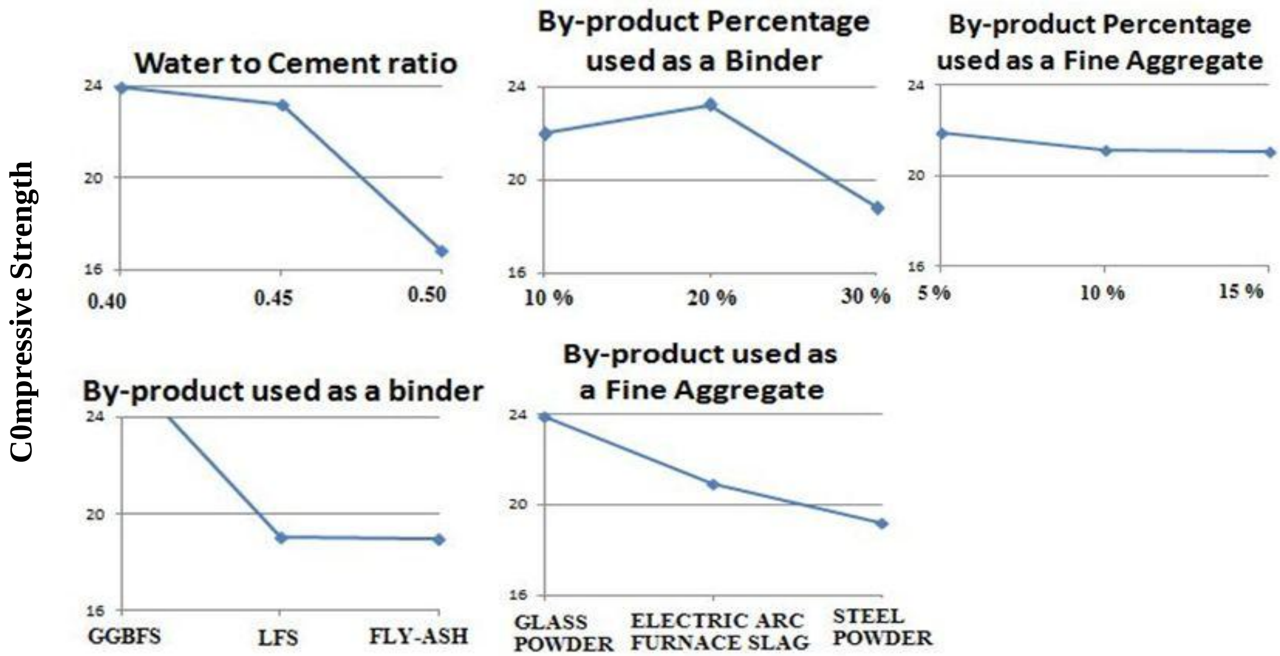


Figure 4.3: Main effects plot for Mean Compressive Strength (7 Days)

Main effects plot for means (28 Days)

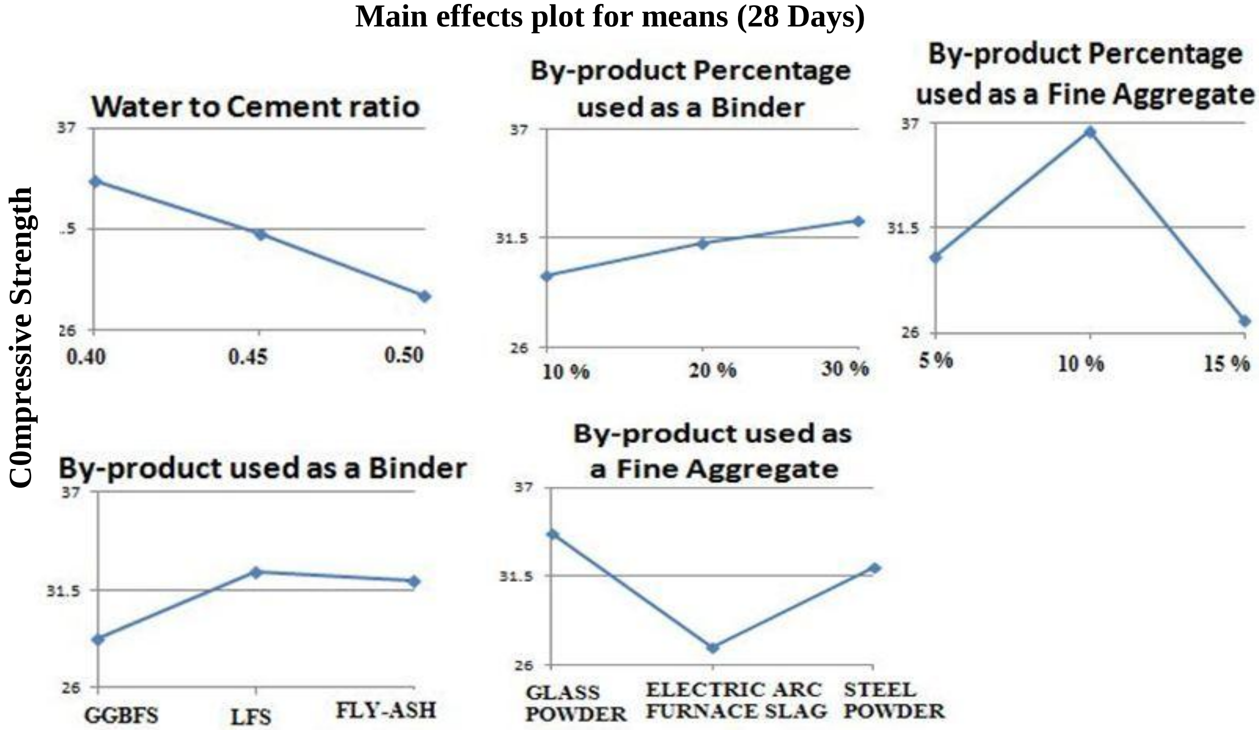


Figure 4.4: Main effects plot for Mean Compressive Strength (28 Days)

Main effects plot for means (56 Days)

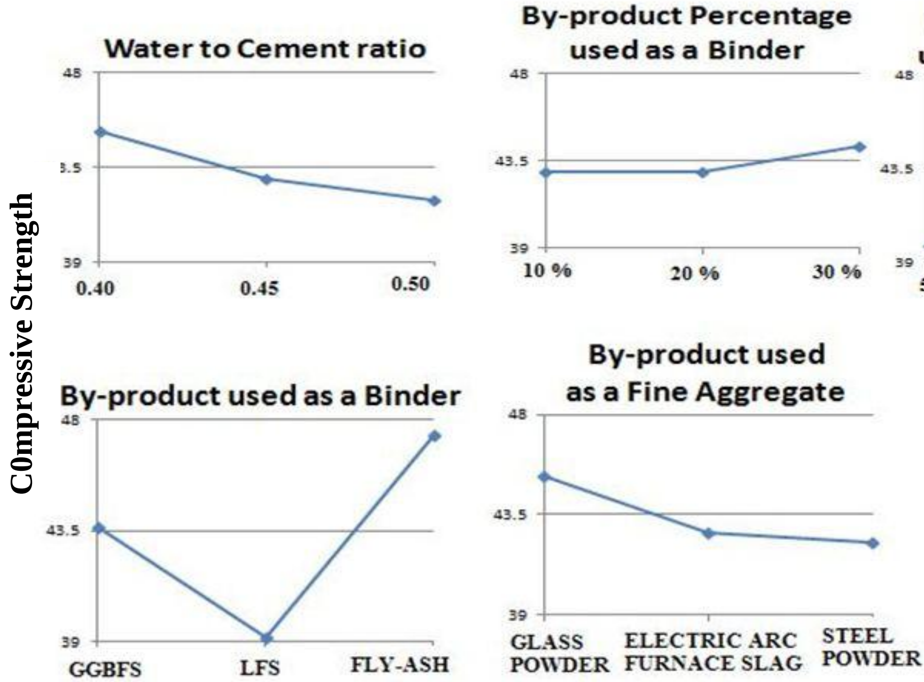


Figure 4.5: Main effects plot for Mean Compressive Strength (56 Days)

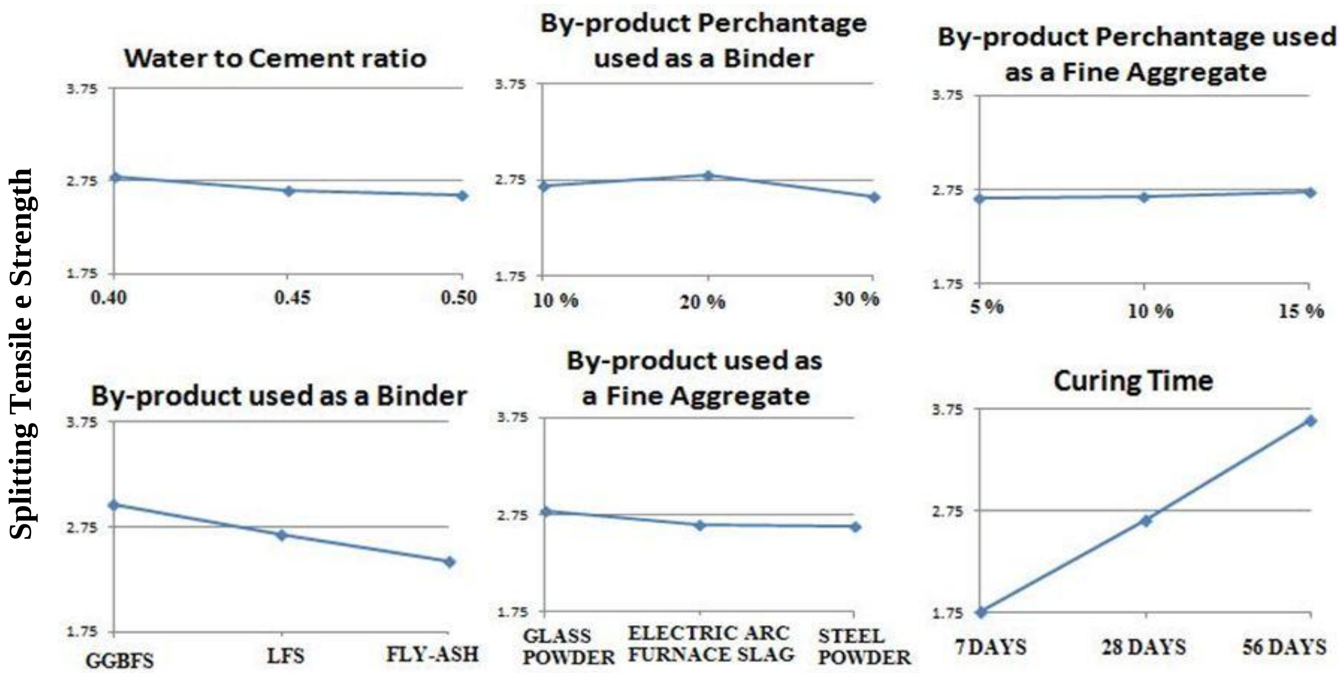


Figure 4.6: Main effects plot for Mean Splitting Tensile Strength

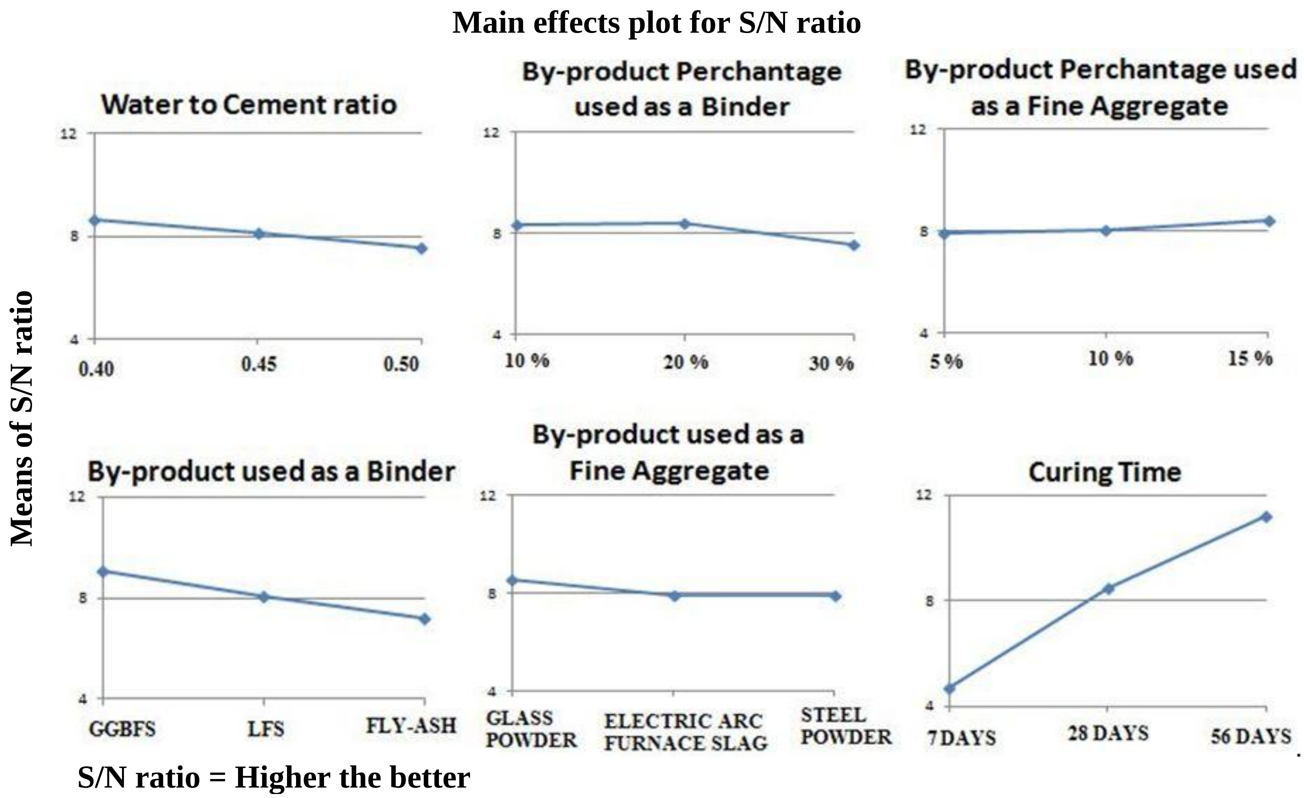


Figure 4.7: Main effects plot for S/N Ratio of Splitting Tensile Strength

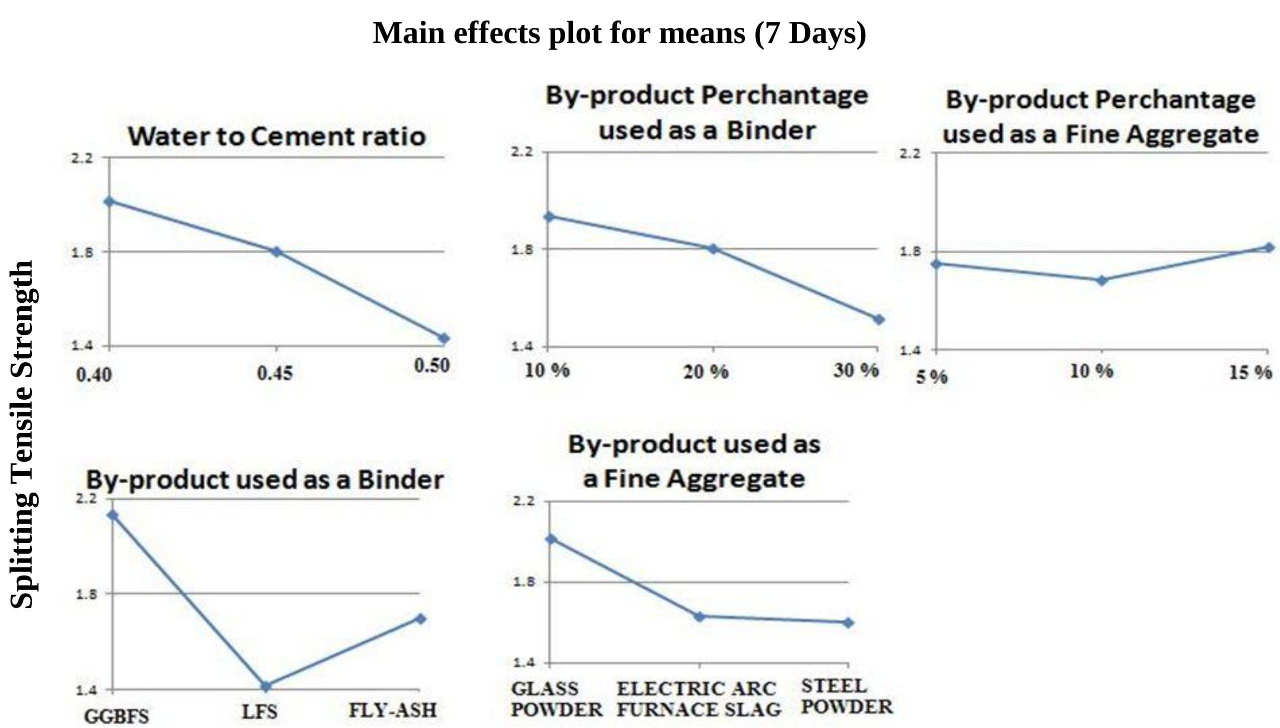


Figure 4.8: Main effects plot for Mean Splitting Tensile Strength (7 Days)

Main effects plot for means (28 Days)

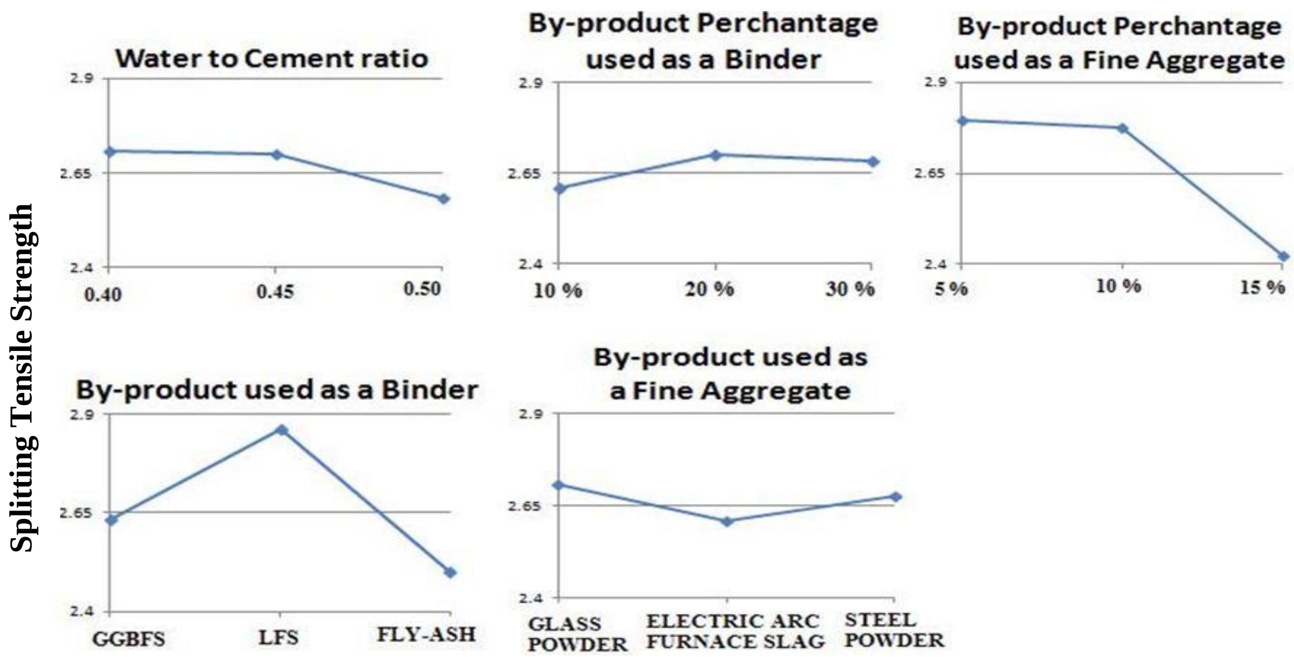


Figure 4.9: Main effects plot for Mean Splitting Tensile Strength (28 Days)

Main effects plot for means (56 Days)

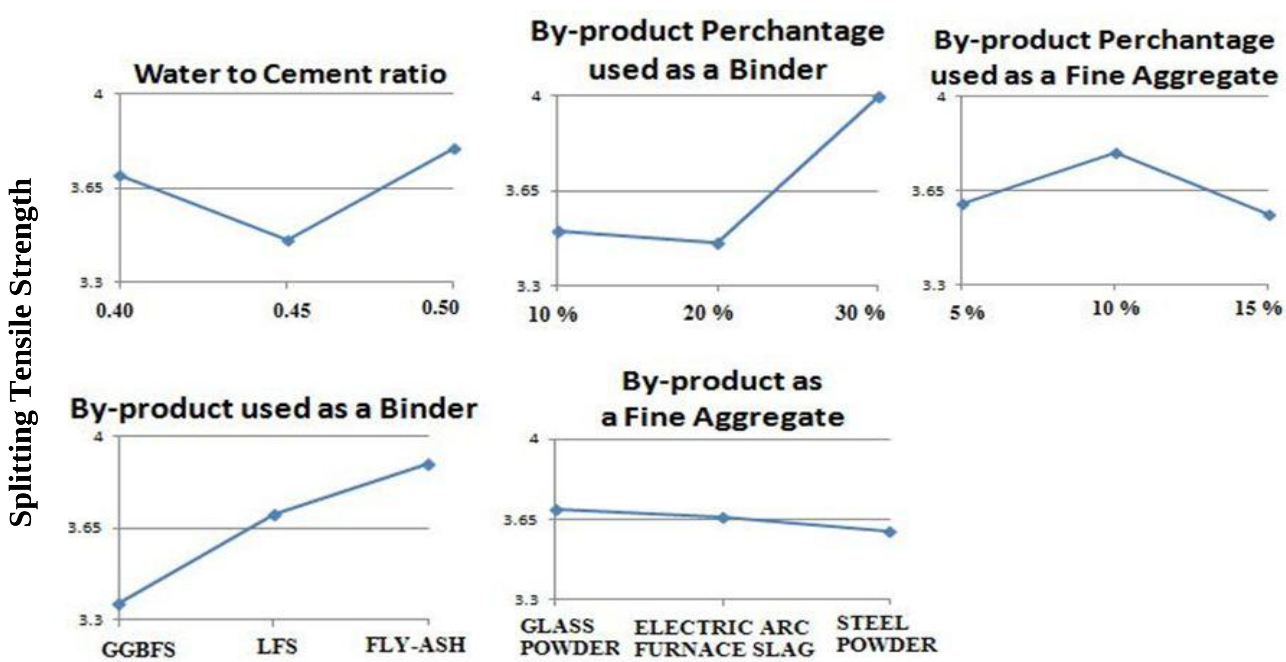


Figure 4.10: Main effects plot for Mean Splitting Tensile Strength (56 Days)

Main effects plot for means

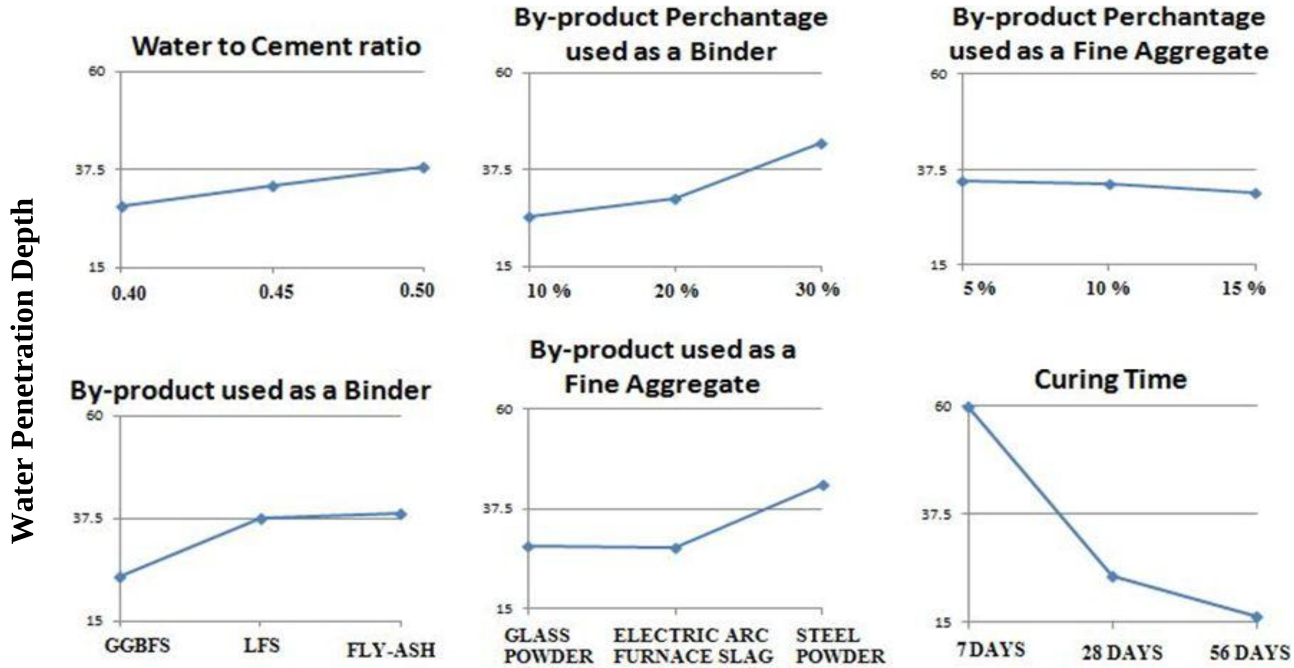


Figure 4.11: Main effects plot for Water Penetration Depth

Main effects plot for means (7 Days)

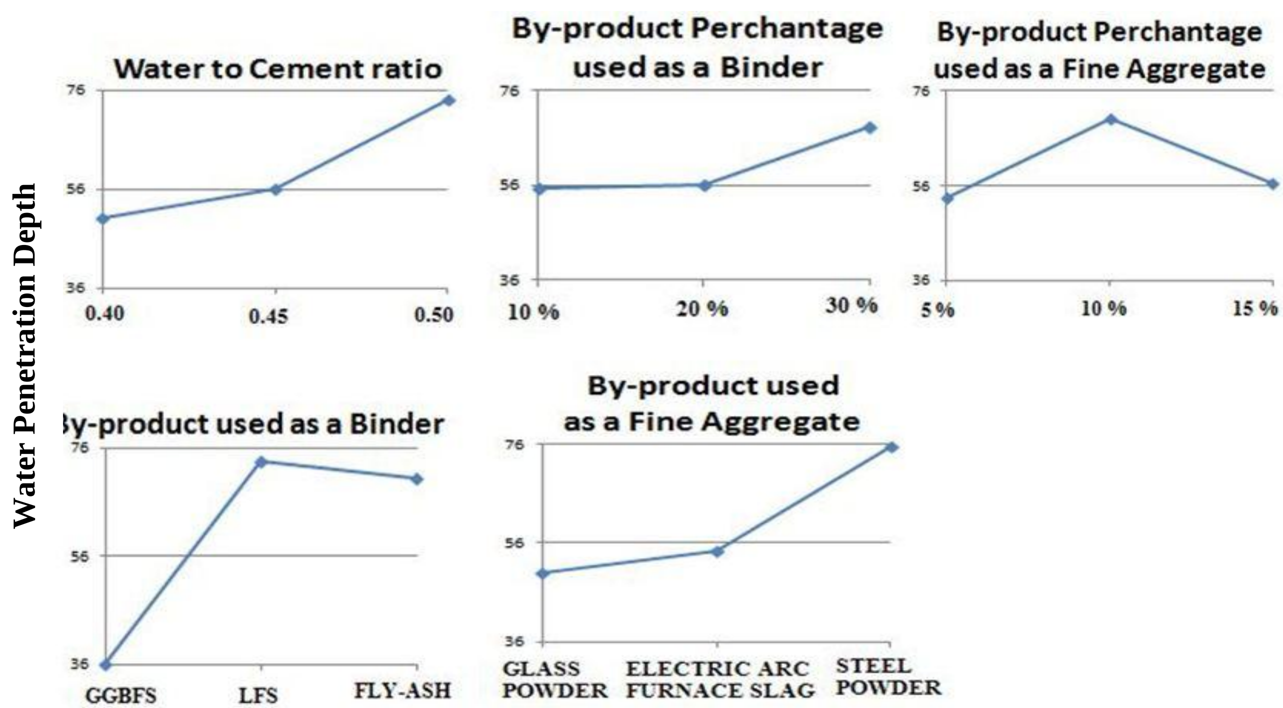


Figure 4.12: Main effects plot for Mean Water Penetration Depth (7 Days)

Main effects plot for means (28 Days)

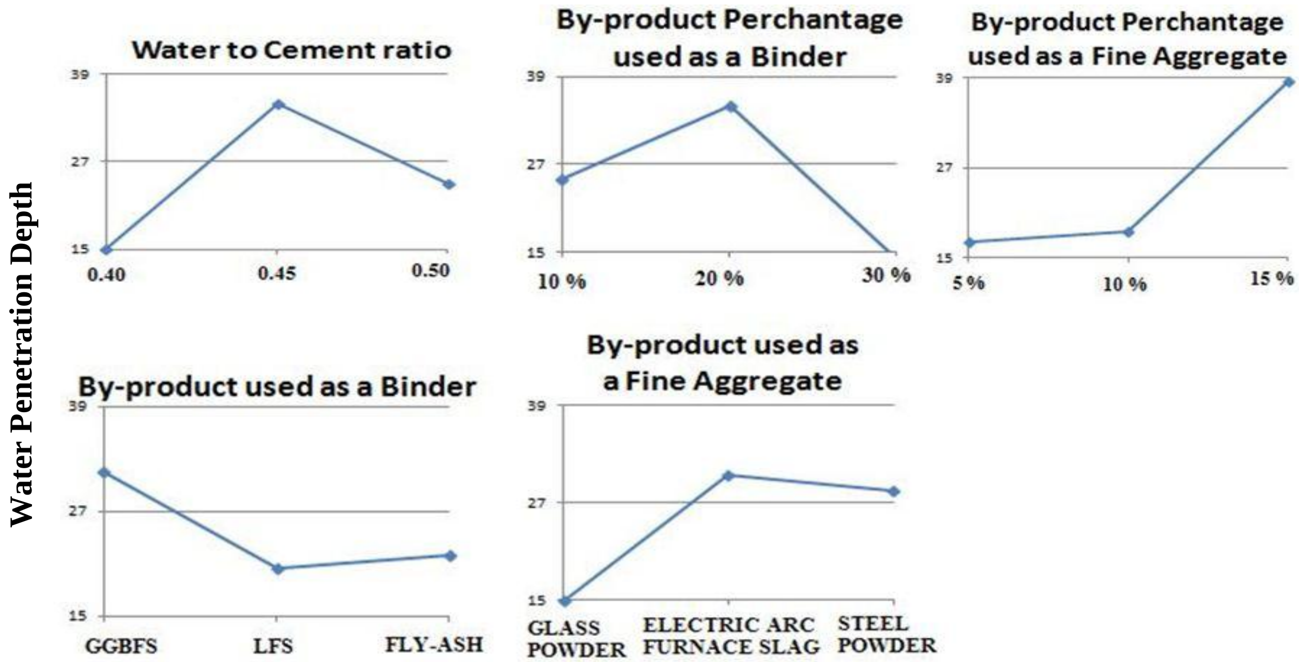


Figure 4.13: Main effects plot for Mean Water Penetration Depth (28 Days)

Main effects plot for means (56 Days)

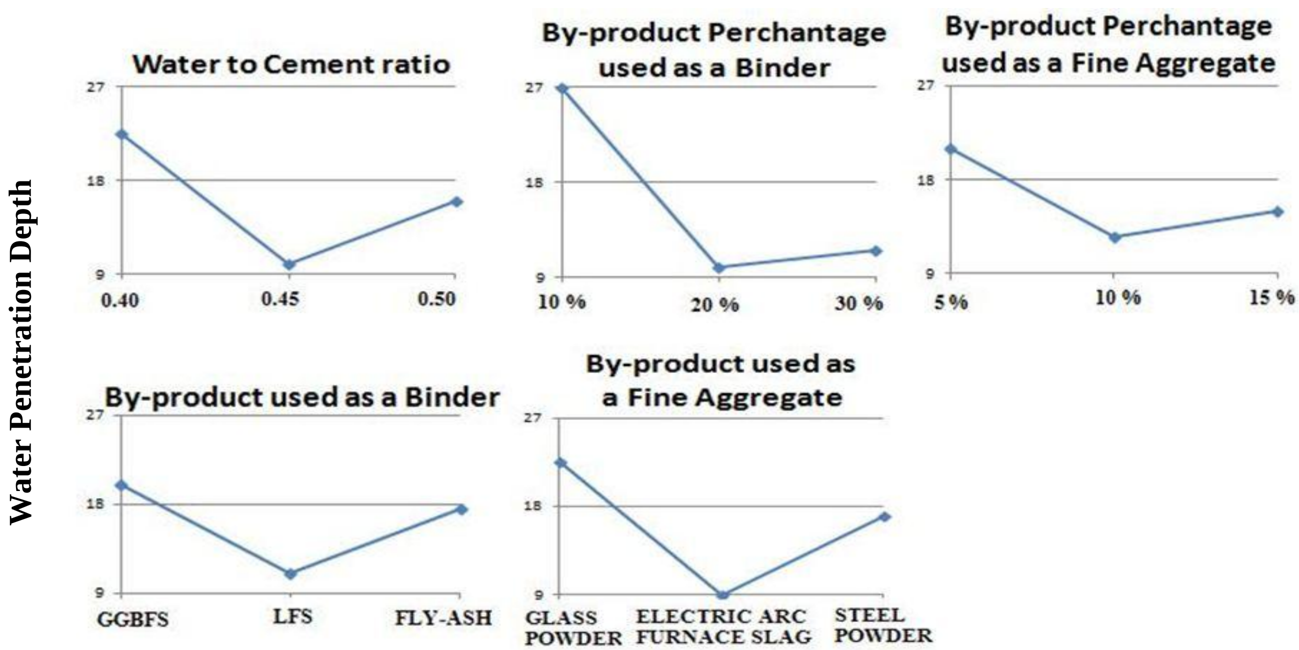


Figure 4.14: Main effects plot for Mean Water Penetration Depth (56 Days)

5.0 GENRAL

The second approach involved the quantities of material are calculated considering the effect of variable specific gravities of the original material and its replacement.

5.1 Analysis of Variance using Approach-2

5.1.1 Analysis of Variance - Compressive Strength

The results of compressive strength for each of the 18 trials with repetitions are given in Table 5.1. ANOVA Table 5.2 shows that curing time (F value 150.490) is the factor that significantly affects the compressive strength followed by type of by-product used as a binder (F value 9.377), type of by-product used as a fine aggregate (F value 7.663) and water to cement Ratio (F value 6.39). All other factors namely by-product percentage used as a binder and by-product percentage used as a fine-aggregate were found to be insignificant. Table 5.3 shows the rank of various factors in the term of their relative significance. Curing time has the highest rank signifying higher contribution to compressive strength and by-product percentage used as a fine aggregate has the lowest rank and was observed to be insignificant in affecting compressive strength. Main effect plot for the mean compressive strength is shown in Figure 5.1 which shows the variation of compressive strength with the input parameters.

5.1.2 Analysis of Variance – Splitting Tensile Strength

The results of splitting tensile strength for each of the 18 trials with repetitions are given in Table 5.12. ANOVA Table 5.13 shows that curing time (F value 113.0) is the factor that significantly affects the splitting tensile strength followed by type of by-product used as a fine-aggregate (F value 9.1678) and by-product percentage used as a binder (F value 6.2178). All other factors namely type of by-product used as a binder, by-product percentage used as a fine-aggregate and water to cement ratio were found to be insignificant. Table 5.14 shows the rank of various factors in the term of their relative significance. Curing time has the highest rank signifying higher contribution to splitting tensile strength and by-product percentage used as a binder has the lowest rank and was observed to be insignificant in affecting splitting tensile strength. Main effect plot for the mean splitting tensile strength is shown in Figure 5.6 which shows the variation of splitting tensile strength with the input parameters.

5.1.3 Analysis of Variance – Water Penetration Depth

The results of water penetration depth for each of the 18 trials with repetitions are given in Table 5.23. ANOVA Table 5.24 shows that curing time (F value 33.2254) is the factor that significantly affects the water penetration depth followed by type of by-product used as a fine aggregate (F value 13.0493), type of by-product used as a binder (F value 10.2099) and by-product percentage used as a binder (F value 8.3369). All other factors namely by-product percentage used as a fine-aggregate and water to cement ratio were found to be insignificant. Table 5.25 shows the rank of various factors in the term of their relative significance. Curing time has the highest rank signifying higher contribution to water penetration depth and by-product percentage used as a fine-aggregate has the lowest rank and was observed to be insignificant in affecting water penetration depth. Main effect plot for the mean water penetration depth is shown in Figure 5.11 which shows the variation of water penetration depth with the input parameters.

5.2 Optimal Design consideration

5.2.1 Compressive Strength

In this experimental analysis, the main effect plot in Figure 5.1 is used to estimate the mean compressive strength with optimal design conditions. In Table 5.6 it is concluded that highest compressive strength was achieve when water to cement ratio 0.40, ground granulated blast furnace slag as a binder, glass powder as a fine aggregate and curing time 56 days were selected. In S/N ratio highest compressive strength was found when water to cement ratio 0.40, ground granulated blast furnace slag (GGBFS) as a binder, glass powder as a fine aggregate and curing time 56 days were selected.

Estimating the mean

Mean value of Compressive Strength is given by:

$\mu_{A1, D1, E1, F3} = \overline{A_1} + \overline{D_1} + \overline{E_1} + \overline{F_3} - 2\overline{T}$

= 32.257+32.925+31.772+41.61 -3(520.4/18)

= 138.564 – 86.73

= 51.83 N/mm^2

Confidence Interval around the Estimating mean

$$n_{eff} = \frac{N}{1+dof_{A1,D1,F3}} = \frac{18}{1+(2+2+2+2)} = 2.0$$

Where N = number of trials in the experiment

$$CI = \sqrt[2]{\frac{6.61*5.95}{2.0}}$$

= ± 4.434 N/mm^2

Thus the confidence interval around the estimated mean of compressive Strength is given by 51.83 ± 4.434 N/mm^2.

5.2.2 Splitting Tensile Strength

In this experimental analysis, the main effect plot in Figure 5.6 is used to estimate the mean splitting tensile strength with optimal design conditions. In Table 5.17 it is concluded that highest splitting tensile strength was achieve when 10% by-product as a binder, glass powder as a fine aggregate and curing time 56 days were selected. In S/N ratio highest splitting tensile strength was found when glass powder as a fine aggregate and curing time 56 days were selected

Estimating the mean

Mean value of Splitting Tensile Strength is given by:

$\mu_{B1, E1, F3} = \overline{B_1} + \overline{E_1} + \overline{F_3} - 2\overline{T}$

= 2.68+2.728 + 3.4 -2(45.65/18)

= 8.808 – 5.07

= 3.74 N/mm^2

Confidence Interval around the Estimating mean

$$n_{eff} = \frac{N}{1+dof_{A1,D1,F3}} = \frac{18}{1+(2+2+2)} = 2.57$$

Where N = number of trials in the experiment

$$CI = \sqrt[2]{\frac{6.61*0.033}{2.57}}$$

$= \pm\ 0.291\ N/mm^2$

Thus the confidence interval around the estimated mean of splitting tensile strength is given by $3.74 \pm 0.291\ N/mm^2$.

5.2.3 Water Penetration Depth

In this experimental analysis, the main effect plot in Figure 5.11 is used to estimate the mean water penetration depth with optimal design conditions. In Table 5.26 it is concluded that lowest water penetration depth was achieve when 20 % Ground granulated blast furnace slag as a binder, electric arc furnace slag as a fine aggregate and curing time 56 days were selected. Water penetration depth is a "Lower the better" type response.

Estimating the mean

Mean value of water penetration depth is given by:

$$\mu_{B1,\ D1,\ E2,\ F3} = \overline{B_2} + \overline{D_1} + \overline{E_2} + \overline{F_3} - 3\overline{T}$$

$$= 29+22.667+25.833 + 19.167 -3(635/18)$$

$$= 96.667 - 35.277$$

$$= 61.39\ mm$$

Confidence Interval around the Estimating mean

$$n_{eff} = \frac{N}{1+dof_{A1,\ D1,\ F3}} = \frac{18}{1+(2+2+2+2)} = 2.0$$

Where N = number of trials in the experiment

$$CI = \sqrt[2]{\frac{6.61*66.91}{2.0}}$$

$= \pm\ 14.87\ mm$

Thus the confidence interval around the estimated mean of Water penetration depth is given by 61.39 ± 14.87 mm.

5.3 Signal to noise ratio (S/N ratio)

5.3.1 Result for S/N ratio - Compressive Strength

Table 5.4 shows the ANOVA results for S/N ratio of compressive strength. Water to cement ratio, type of by-product used as a binder, type of by-product used as a fine aggregate and curing time are found to significant. According to F-test curing time (F value 132.38) was found to be most significant factor affecting the compressive strength followed by type of by-product used as a binder (F value 10.986), type of by-product used as a fine aggregate (F value 10.186) and water to cement ratio (F value 9.711). Main effect plot of S/N ratio for compressive strength are shown in Figure 5.2. Table 5.5 shows the ranks of various factors in the terms of their relative significance. Curing time has the highest rank which signifies that it provides highest contribution to compressive strength and by-product percentage used as a fine aggregate has the lowest rank and was found to be insignificant in affecting compressive strength.

5.3.2 Result for S/N ratio - Splitting Tensile Strength

Table 5.15 shows the ANOVA results for S/N ratio of splitting tensile strength. Type of by-product used as a fine aggregate and curing time was observed to be most significant factors affecting the splitting tensile strength. According to F-test curing time (F value 80.83) was found to be most significant factor affecting the splitting tensile strength followed by type of by-product used as a fine aggregate (F value 5.85). Main effect plot of S/N ratio for splitting tensile strength are shown in Figure 5.7. Table 5.16 shows the ranks of various factors in the terms of their relative significance. Curing time has the highest rank which signifies that it provides highest contribution to splitting tensile strength and by-product percentage used as a binder has the lowest rank and was found to be insignificant in affecting splitting tensile strength.

5.4 Effect of Curing Time

5.4.1 Effect of Curing Time on Compressive Strength

Results for compressive strength after 7 days, 28 days and 56 days of curing are shown in Table 5.7. The Response table for means of compressive strength using the results of Table 5.7 for 7 days, 28 days and 56 days was calculated and shown in Table 5.8, 5.9 and 5.10 respectively. Finally the significant factors for compressive strength for each part i.e. 7 days, 28 days and 56 days were given in Table 5.11.

Optimal Design considering Effect of Curing Time

In this experimental analysis, the main effect in Figure 5.3, 5.4 and 5.5 are used to estimate the mean compressive strength with optimal design condition for 7days, 28 days and 56 days of curing time respectively. In Table 5.11 it is concluded that highest compressive strength was achieved for 7 days when water to cement ratio 0.40, 10% granulated blast furnace slag as a binder and 5% glass powder as a fine aggregate were selected. From Table 4.48 the highest compressive strength was achieved for 28 days when water to cement ratio 0.40, 30% Fly-ash as a binder and 10% glass powder as a fine aggregate were selected. For 56 days the highest compressive strength was achieved when water to cement ratio 0.40, 30% fly-ash as a binder and 15% Steel powder as a fine aggregate were selected.

5.4.2 Effect of Curing Time on Splitting Tensile Strength

Results for splitting tensile strength after 7 days, 28 days and 56 days of curing are shown in Table 5.18. The Response table for means of splitting tensile strength using the results of Table 5.18 for 7 days, 28 days and 56 days was calculated and shown in Table 5.19, 5.20 and 5.21 respectively. Finally the significant factors for splitting tensile strength for each part i.e. 7 days, 28 days and 56 days were given in Table 5.22.

Optimal Design considering Effect of Curing Time

In this experimental analysis, the main effect in Figure 5.8, 5.9 and 5.10 are used to estimate the mean splitting tensile strength with optimal design condition for 7days, 28 days and 56 days of curing time respectively. In Table 5.22 it is concluded that highest splitting tensile strength was achieved for 7 days when water to cement ratio 0.40, 10% granulated blast furnace slag as a binder and 10% glass powder as a fine aggregate were selected. From Table 4.59 the highest splitting tensile strength was achieved for 28 days when water to cement ratio 0.40, 10% fly-ash as a binder and 10% glass powder as a fine aggregate were selected. For 56 days the highest splitting tensile strength was achieved when water to cement ratio 0.40, 10% ladle furnace slag as a binder and 15% Electric arc furnace slag as a fine aggregate were selected.

5.4.3 Effect of Curing Time on Water Penetration Depth

Results for water penetration depth after 7 days, 28 days and 56 days of curing are shown in Table 5.27. The Response table for means of water penetration depth using the results of Table 5.27 for 7 days, 28 days and 56 days was calculated and shown in Table 5.28, 5.29 and 5.30 respectively. Finally the significant factors for water penetration depth for each part i.e. 7 days, 28 days and 56 days were given in Table 5.31.

Optimal Design considering Effect of Curing Time

The main effect in Figure 5.12, 5.13 and 5.14 are used to estimate the mean water penetration depth with optimal design condition for 7days, 28 days and 56 days of curing time respectively. In Table 5.31 it is concluded that lowest water penetration depth was achieved for 7 days when water to cement ratio 0.45, 20% Granulated blast furnace slag as a binder and 15% Electric arc furnace slag as a fine aggregate were selected. The lowest water penetration depth was achieved for 28 days when water to cement ratio 0.40, 10% Fly-ash as a binder and 5% Glass powder as a fine aggregate were selected. For 56 days the lowest water penetration depth was achieved when water to cement ratio 0.45, 20% LFS as a binder and 15% Steel powder as a fine aggregate were selected.

Table 5.1 Results for Compressive Strength (Approach -2)

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Compressive Strength			Mean	S/N Ratio
							I	II	III		
1	0.40	10%	5	GGBFS	Glass Powder	7	26.59	26.72	27.13	26.8	28.56
2	0.40	20%	10	FLY-ASH	EAFS	28	27.66	29.55	31.02	29.41	29.34
3	0.40	30%	15	LFS	Steel Powder	56	37.80	37.50	36.02	37.52	31.38
4	0.45	10%	5	FLY-ASH	EAFS	56	43.21	39.20	40.10	40.8	32.19
5	0.45	20%	10	LFS	Steel Powder	7	17.93	18.25	17.98	18.05	25.13
6	0.45	30%	15	GGBFS	Glass Power	28	34.06	31.80	35.12	33.7	30.51
7	0.50	10%	10	GGBFS	Steel Powder	28	27.13	27.37	27.12	27.2	28.69
8	0.50	20%	15	FLY-ASH	Glass Power	56	40.41	39.97	39.50	39.94	32.03
9	0.50	30%	5	LFS	EAFS	7	13.80	14.20	14.70	14.23	23.05
10	0.40	10%	15	LFS	EAFS	28	32.72	36.18	36.40	36.54	30.87
11	0.40	20%	5	GGBFS	Steel Powder	56	45.18	44.43	44.45	44.7	33.00
12	0.40	30%	10	FLY-ASH	Glass Power	7	19.93	20.44	19.74	20.04	26.03
13	0.45	10%	10	LFS	Glass Power	56	40.92	46.53	41.40	42.95	32.61
14	0.45	20%	15	GGBFS	EAFS	7	21.36	21.46	21.38	21.4	26.60
15	0.45	30%	5	FLY-ASH	Steel Powder	28	20.50	20.86	20.81	20.71	26.32
16	0.50	10%	15	FLY-ASH	Steel Powder	7	13.40	13.34	13.32	13.35	22.51
17	0.50	20%	5	LFS	Glass Power	28	26.71	26.90	28.06	27.2	28.69
18	0.50	30%	10	GGBFS	EAFS	56	44.88	42.46	43.88	43.75	32.81

Table 5.2 ANOVA for means of Compressive Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio(A)	65.303	2	32.651	6.39	5.79	53.4	3.550
By-product as a Binder used (Percent) (B)	22.788	2	11.394	2.219	5.79		1.239
By-product as a Fine Aggregate used (Percent) (C)	5.122	2	2.561	0.498	5.79		0.278
By-product used as a Binder(D)	96.288	2	48.144	9.377	5.79	84.38	5.235
By-product used as a Fine Aggregate(E)	78.69	2	39.345	7.663	5.79	66.79	4.278
Curing Time (Days) (F)	1545.66	2	772.604	150.490	5.79	1533.7	84.021
Error	25.669	5	5.133				1.395
Total	1839.07	17					100
e pooled	53.579	9	5.95			100.74	1.517

Table 5.3 Response table for means of Compressive Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	32.257	31.028	29.068	32.925	31.772	18.973
2	29.602	30.117	30.233	27.375	30.772	28.882
3	27.607	28.320	30.163	29.165	26.922	41.61
Delta	4.65	2.708	1.165	5.55	4.85	22.637
Rank	4	5	6	2	3	1

Table 5.4 ANOVA for S/N Ratio of Compressive Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio(A)	10.830	2	5.415	9.711	5.79	9.432	5.732
By-product as a Binder used (Percent) (B)	2.810	2	1.405	2.520	5.79		1.487
By-product as a Fine Aggregate used (Percent) (C)	0.696	2	0.348	0.624	5.79		0.368
By-product used as a Binder(D)	12.250	2	6.126	10.986	5.79	9.589	6.485
By-product used as a Fine Aggregate(E)	11.350	2	5.676	10.180	5.79	8.78	6.009
Curing Time (Days) (F)	148.1	2	74.09	132.88	5.79	131.48	78.439
Error	2.788	5	0.557				1.475
Total	188.9	17					100
e pooled	6.294	9	0.699			29.619	3.33

Table 5.5 Response table for S/N Ratio of Compressive Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	29.866	29.242	28.641	30.033	29.743	25.317
2	28.900	29.134	29.104	28.074	29.147	29.074
3	27.966	28.355	28.987	28.625	27.841	32.340
Delta	1.899	0.887	0.463	1.959	1.901	7.022
Rank	4	5	6	2	3	1

Table 5.6 Significant factors for Compressive Strength

Factors	Affecting mean		Affecting variation (S/N ratio)	
	Contribution	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 1- 0.40	Significant	Level 1- 0.40
By-product as a Binder used (Percent)	Insignificant	-	Insignificant	-
By-product as a Fine aggregate used (Percent)	Insignificant	-	Insignificant	-
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 1- GGBFS
By-product used as a Fine Aggregate	Insignificant	Level 1- Glass Powder	Significant	Level 1- Glass Powder
Curing Time (Days)	Significant	Level 3- 56 Days	Significant	Level 3- 56 Days

Table 5.7 Results for Compressive Strength according to curing time

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Compressive Strength			Mean	S/N Ratio
							I	II	III		
1	0.40	10%	5	GGBFS	Glass Powder	7 DAYS	26.59	26.72	27.13	26.8	28.56
2	0.45	20%	10	LFS	Steel Powder		17.93	18.25	17.98	18.05	25.13
3	0.50	30%	5	LFS	EAFS		13.80	14.20	14.70	14.23	23.05
4	0.40	30%	10	FLY-ASH	Glass Power		19.93	20.44	19.74	20.04	26.03
5	0.45	20%	15	GGBFS	EAFS		21.36	21.46	21.38	21.4	26.60
6	0.50	10%	15	FLY-ASH	Steel Powder		13.40	13.34	13.32	13.35	22.51
1	0.40	20%	10	FLY-ASH	EAFS	28 DAYS	27.66	29.55	31.02	29.41	29.34
2	0.45	30%	15	GGBFS	Glass Power		34.06	31.80	35.12	33.7	30.51
3	0.50	10%	10	GGBFS	Steel Powder		27.13	27.37	27.12	27.2	28.69
4	0.40	10%	15	LFS	EAFS		32.72	36.18	36.40	36.54	30.87
5	0.45	30%	5	FLY-ASH	Steel Powder		20.50	20.86	20.81	20.71	26.32
6	0.50	20%	5	LFS	Glass Power		26.71	26.90	28.06	27.2	28.69
1	0.40	30%	15	LFS	Steel Powder	56 DAYS	37.80	37.50	36.02	37.52	31.38
2	0.45	10%	5	FLY-ASH	EAFS		43.21	39.20	40.10	40.8	32.19
3	0.50	20%	15	FLY-ASH	Glass Power		40.41	39.97	39.50	39.94	32.03
4	0.40	20%	5	GGBFS	Steel Powder		45.18	44.43	44.45	44.7	33.00
5	0.45	10%	10	LFS	Glass Power		40.92	46.53	41.40	42.95	32.61
6	0.50	30%	10	GGBFS	EAFS		44.88	42.46	43.88	43.75	32.81

Table 5.8 Response table for means of Compressive Strength (7 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	23.42	20.075	20.5	24.1	23.42
2	19.725	19.725	19.045	16.125	17.8
3	13.775	17.12	17.375	16.695	15.7
Delta	9.645	2.955	3.125	7.975	7.72
Rank	1	5	4	2	3

Table 5.9 Response table for means of Compressive Strength (28 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	32.44	28.305	28.305	25.06	32.24
2	27.205	27.205	34.385	30.45	23.995
3	27.2	31.135	23.955	31.135	30.45
Delta	5.04	3.93	10.43	6.075	8.285
Rank	4	5	1	3	2

Table 5.10 Response table for means of Compressive Strength (56 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	41.11	40.635	38.73	40.235	41.11
2	41.875	41.875	42.75	40.37	41.445
3	41.845	42.32	43.35	44.225	42.275
Delta	0.765	1.685	4.62	3.99	1.165
Rank	5	3	1	2	4

Table 5.11 Significant factors for Compressive Strength

Factors	Affecting mean (7 Days)		Affecting mean (28 Days)		Affecting mean (56 Days)	
	Contribution	**Best Level**	**Contribution**	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 1- 0.40	Significant	Level 1- 0.40	Significant	Level 1- 0.40
By-product as a Binder used (Percent)	Significant	Level 1- 10 %	Significant	Level 3- 30 %	Significant	Level 3- 30 %
By-product as a Fine aggregate used (Percent)	Significant	Level 1- 5 %	Significant	Level 2- 10 %	Significant	Level 3- 15 %
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 3- FLY-ASH	Significant	Level 3- FLY-ASH
By-product used as a Fine Aggregate	Significant	Level 1- Glass Powder	Significant	Level 1- Glass Powder	Significant	Level 3- Steel Powder

Table 5.12 Results for Splitting Tensile Strength

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Splitting Tensile Strength		Mean	S/N Ratio
							I	II		
1	0.40	10%	5	GGBFS	Glass Powder	7	1.98	1.92	1.95	5.79
2	0.40	20%	10	FLY-ASH	EAFS	28	2.9	2.7	2.8	8.92
3	0.40	30%	15	LFS	Steel Powder	56	2.76	2.93	2.85	9.07
4	0.45	10%	5	FLY-ASH	EAFS	56	3.64	3.57	3.61	11.13
5	0.45	20%	10	LFS	Steel Powder	7	1.83	1.91	1.87	3.94
6	0.45	30%	15	GGBFS	Glass Power	28	2.55	2.75	2.65	8.44
7	0.50	10%	10	GGBFS	Steel Powder	28	2.32	2.35	2.34	7.36
8	0.50	20%	15	FLY-ASH	Glass Power	56	3.76	3.42	3.6	11.07
9	0.50	30%	5	LFS	EAFS	7	1.1	1.2	1.15	1.18
10	0.40	10%	15	LFS	EAFS	28	3.24	3.61	3.43	9.76
11	0.40	20%	5	GGBFS	Steel Powder	56	3.35	3.21	3.3	10.31
12	0.40	30%	10	FLY-ASH	Glass Power	7	1.76	1.78	1.77	4.95
13	0.45	10%	10	LFS	Glass Power	56	3.51	3.63	3.6	11.04
14	0.45	20%	15	GGBFS	EAFS	7	1.73	1.7	1.72	4.68
15	0.45	30%	5	FLY-ASH	Steel Powder	28	1.88	1.93	1.91	5.59
16	0.50	10%	15	FLY-ASH	Steel Powder	7	1.5	1.44	1.5	3.34
17	0.50	20%	5	LFS	Glass Power	28	2.65	2.95	2.8	8.90
18	0.50	30%	10	GGBFS	EAFS	56	3.65	3.24	3.44	10.69

Table 5.13 ANOVA for means of Splitting Tensile Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio (A)	0.0759	2	0.0379	0.8909	5.79		0.6717
By-product as a Binder used (Percent)(B)	0.5297	2	0.2648	6.2178	5.79	0.464	4.6879
By-product as a Fine Aggregate used (Percent) (C)	0.0630	2	0.0315	0.7403	5.79		0.5582
By-product used as a Binder(D)	0.0098	2	0.0049	0.1151	5.79		0.0868
By-product used as a Fine Aggregate(E)	0.7810	2	0.3905	9.1678	5.79	0.715	6.9121
Curing Time (Days) (F)	9.6274	2	4.8137	113.00	5.79	9.56	85.1981
Error	0.2129	5	0.0425				1.8849
Total	11.300	17					100
e pooled	0.3616	11	0.033			0.559	3.202

Table 5.14 Response table for means of Splitting Tensile Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	2.625	2.68	2.453	2.566	2.728	1.611
2	2.511	2.633	2.588	2.531	2.633	2.596
3	2.471	2.295	2.566	2.51	2.246	3.4
Delta	0.153	0.385	0.135	0.056	0.4817	1.788
Rank	4	3	5	6	2	1

Table 5.15 ANOVA for S/N Ratio of Splitting Tensile Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio (A)	3.3418	2	1.6709	2.0353	5.79		2.0910
By-product as a Binder used (Percent) (B)	7.4880	2	3.7440	4.5605	5.79		4.6854
By-product as a Fine Aggregate used (Percent) (C)	1.5677	2	0.7838	0.9548	5.79		0.9809
By-product used as a Binder(D)	0.9885	2	0.4942	0.6020	5.79		0.6185
By-product used as a Fine Aggregate(E)	9.6071	2	4.8035	5.8510	5.79	6.91	6.0113
Curing Time (Days) (F)	132.71	2	66.3588	80.8297	5.79	130.0	83.0440
Error	4.1048	5	0.8209				2.5684
Total	159.815	17					100
e pooled	17.5	13	1.345			22.88	10.9447

Table 5.16 Response table for S/N Ratio of Splitting Tensile Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	8.1382	8.0758	7.1561	7.8838	8.3719	3.9861
2	7.4764	7.9744	7.8239	7.5053	7.7332	8.1673
3	7.0952	6.6597	7.7298	7.3208	6.6048	10.556
Delta	1.0429	1.4161	0.6678	0.563	1.7671	6.5703
Rank	4	3	5	6	2	1

Table 5.17 Significant factors for Splitting Tensile Strength

Factors	Affecting mean		Affecting variation (S/N ratio)	
	Contribution	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Insignificant	-	Insignificant	-
By-product as a Binder used (Percent)	Significant	Level 1-10 %	Insignificant	-
By-product as a Fine aggregate used (Percent)	Insignificant	-	Insignificant	-
By-product used as a Binder	Insignificant	-	Insignificant	-
By-product used as a Fine Aggregate	Significant	Level 1- Glass Powder	Significant	Level 1- Glass Powder
Curing Time (Days)	Significant	Level 3- 56 Days	Significant	Level 3- 56 Days

Table 5.18 Results for Splitting Tensile Strength according to curing time

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Splitting Tensile Strength		Mean	S/N Ratio
							I	II		
1	0.40	10%	5	GGBFS	Glass Powder	7 DAYS	1.98	1.92	1.95	5.79
2	0.45	20%	10	LFS	Steel Powder		1.83	1.91	1.87	3.94
3	0.50	30%	5	LFS	EAFS		1.1	1.2	1.15	1.18
4	0.40	30%	10	FLY-ASH	Glass Power		1.76	1.78	1.77	4.95
5	0.45	20%	15	GGBFS	EAFS		1.73	1.7	1.72	4.68
6	0.50	10%	15	FLY-ASH	Steel Powder		1.5	1.44	1.5	3.34
1	0.40	20%	10	FLY-ASH	EAFS	28 DAYS	2.9	2.7	2.8	8.92
2	0.45	30%	15	GGBFS	Glass Power		2.55	2.75	2.65	8.44
3	0.50	10%	10	GGBFS	Steel Powder		2.32	2.35	2.34	7.36
4	0.40	10%	15	LFS	EAFS		3.24	3.61	3.43	9.76
5	0.45	30%	5	FLY-ASH	Steel Powder		1.88	1.93	1.91	5.59
6	0.50	20%	5	LFS	Glass Power		2.65	2.95	2.8	8.90
1	0.40	30%	15	LFS	Steel Powder	56 DAYS	2.76	2.93	2.85	9.07
2	0.45	10%	5	FLY-ASH	EAFS		3.64	3.57	3.61	11.13
3	0.50	20%	15	FLY-ASH	Glass Power		3.76	3.42	3.6	11.07
4	0.40	20%	5	GGBFS	Steel Powder		3.35	3.21	3.3	10.31
5	0.45	10%	10	LFS	Glass Power		3.51	3.63	3.6	11.04
6	0.50	30%	10	GGBFS	EAFS		3.65	3.24	3.44	10.69

Table 5.19 Response table for means of Splitting Tensile Strength (7 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	1.86	1.725	1.55	1.835	1.86
2	1.65	1.65	1.675	1.365	1.435
3	1.325	1.46	1.61	1.635	1.54
Delta	0.535	0.265	0.125	0.47	0.425
Rank	1	4	5	2	3

Table 5.20 Response table for means of Splitting Tensile Strength (28 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	2.94	2.8	2.57	2.355	2.94
2	2.28	2.28	2.865	2.495	2.125
3	2.57	2.71	2.355	2.94	2.725
Delta	0.66	0.52	0.55	0.585	0.815
Rank	2	4	5	3	1

Table 5.21 Response table for means of Splitting Tensile Strength (56 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	3.075	3.145	3.225	3.225	3.075
2	3.605	3.605	3.455	3.605	3.6
3	3.52	3.45	3.52	3.37	3.525
Delta	0.53	0.46	0.295	0.38	0.525
Rank	2	3	5	4	1

Table 5.22 Significant factors for Splitting Tensile Strength

Factors	Affecting mean (7 Days)		Affecting mean (28 Days)		Affecting mean (56 Days)	
	Contribution	**Best Level**	**Contribution**	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 1- 0.40	Significant	Level 1- 0.40	Significant	Level 1- 0.40
By-product as a Binder used (Percent)	Significant	Level 1- 10 %	Significant	Level 1- 10 %	Significant	Level 1- 10 %
By-product as a Fine aggregate used (Percent)	Significant	Level 2- 10 %	Significant	Level 2- 10 %	Significant	Level 3- 15 %
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 3- FLY-ASH	Significant	Level 2- LFS
By-product used as a Fine Aggregate	Significant	Level 1- Glass Powder	Significant	Level 1- Glass Powder	Significant	Level 2- EAFS

Table 5.23 Results for Water Penetration Depth

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Water Penetration Depth
1	0.40	10%	5	GGBFS	Glass Powder	7	32
2	0.40	20%	10	FLY-ASH	EAFS	28	18
3	0.40	30%	15	LFS	Steel Powder	56	35
4	0.45	10%	5	FLY-ASH	EAFS	56	10
5	0.45	20%	10	LFS	Steel Powder	7	78
6	0.45	30%	15	GGBFS	Glass Power	28	25
7	0.50	10%	10	GGBFS	Steel Powder	28	24
8	0.50	20%	15	FLY-ASH	Glass Power	56	20
9	0.50	30%	5	LFS	EAFS	7	68
10	0.40	10%	15	LFS	EAFS	28	19
11	0.40	20%	5	GGBFS	Steel Powder	56	15
12	0.40	30%	10	FLY-ASH	Glass Power	7	68
13	0.45	10%	10	LFS	Glass Power	56	15
14	0.45	20%	15	GGBFS	EAFS	7	20
15	0.45	30%	5	FLY-ASH	Steel Powder	28	65
16	0.50	10%	15	FLY-ASH	Steel Powder	7	80
17	0.50	20%	5	LFS	Glass Power	28	23
18	0.50	30%	10	GGBFS	EAFS	56	20

Table 5.24 ANOVA for Water Penetration Depth

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio	192.444	2	96.222	1.3316	5.79		1.9303
By-product as a Binder used (Percent)	1204.77	2	602.388	8.3369	5.79	1070.9	12.0845
By-product as a Fine Aggregate used (Percent)	48.444	2	24.222	0.3352	5.79		0.4859
By-product used as a Binder	1475.44	2	737.722	10.2099	5.79	1341.6	14.7994
By-product used as a Fine Aggregate	1885.77	2	942.88	13.0493	5.79	1751.9	18.9152
Curing Time (Days)	4801.44	2	2400.72	33.2254	5.79	4667.6	48.1607
Error	361.277	5	72.255				3.6237
Total	9969.61	17					100
e pooled	602.16	9	66.91			1137.6	6.0399

Table 5.25 Response table for Water Penetration Depth

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)
1	31.167	30	35.5	22.667	30.5	57.667
2	35.5	29	37.167	43.5	25.833	29
3	39.167	46.833	33.167	39.667	49.5	19.167
Delta	8	17.833	4	20.833	23.667	38.5
Rank	5	4	6	3	2	1

Table 5.26 Significant factors for Water Penetration Depth

Factors	Affecting mean	
	Contribution	Best Level
Water to Cement ratio	Insignificant	-
By-product as a Binder used (Percent)	Significant	Level 2-20 %
By-product as a Fine aggregate used (Percent)	Insignificant	-
By-product used as a Binder	Significant	Level 1-GGBFS
By-product used as a Fine Aggregate	Significant	Level 2-EAFS
Curing Time (Days)	Significant	Level 3- 56 Days

Table 5.27 Results for Water Penetration Depth

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time (Days)	Water Penetration Depth
1	0.40	10%	5	GGBFS	Glass Powder	7 DAYS	32
2	0.45	20%	10	LFS	Steel Powder		78
3	0.50	30%	5	LFS	EAFS		68
4	0.40	30%	10	FLY-ASH	Glass Power		68
5	0.45	20%	15	GGBFS	EAFS		20
6	0.50	10%	15	FLY-ASH	Steel Powder		80
1	0.40	20%	10	FLY-ASH	EAFS	28 DAYS	18
2	0.45	30%	15	GGBFS	Glass Power		25
3	0.50	10%	10	GGBFS	Steel Powder		24
4	0.40	10%	15	LFS	EAFS		19
5	0.45	30%	5	FLY-ASH	Steel Powder		65
6	0.50	20%	5	LFS	Glass Power		23
1	0.40	30%	15	LFS	Steel Powder	56 DAYS	35
2	0.45	10%	5	FLY-ASH	EAFS		10
3	0.50	20%	15	FLY-ASH	Glass Power		20
4	0.40	20%	5	GGBFS	Steel Powder		15
5	0.45	10%	10	LFS	Glass Power		15
6	0.50	30%	10	GGBFS	EAFS		20

Table 5.28 Response table for means of Water Penetration Depth (7 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	50	56	50	26	50
2	49	49	73	73	44
3	74	68	50	74	79
Delta	25	19	23	48	35
Rank	3	5	4	1	2

Table 5.29 Response table for means of Water Penetration Depth (28 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	18.5	20.5	21	41.5	18.5
2	45	45	22	24.5	44.5
3	23.5	21.5	44	21	24
Delta	26.5	24.5	23	20.5	26
Rank	1	3	4	5	2

Table 5.30 Response table for means of Water Penetration Depth (56 Days)

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	25	27.5	27.5	25	25
2	12.5	12.5	12.5	15	17.5
3	20	17.5	17.5	17.5	15
Delta	12.5	15	15	10	10
Rank	3	1	2	4	5

Table 5.31 Significant factors for Water Penetration Depth

Factors	Affecting mean (7 Days)		Affecting mean (28 Days)		Affecting mean (56 Days)	
	Contribution	Best Level	Contribution	Best Level	Contribution	Best Level
Water to Cement ratio	Significant	Level 2- 0.45	Significant	Level 1- 0.40	Significant	Level 2- 0.45
By-product as a Binder used (Percent)	Significant	Level 2- 20 %	Significant	Level 1- 10 %	Significant	Level 2- 20 %
By-product as a Fine aggregate used (Percent)	Significant	Level 3- 15 %	Significant	Level 1- 5 %	Significant	Level 2- 10 %
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 3- Fly-ash	Significant	Level 2- LFS
By-product used as a Fine Aggregate	Significant	Level 2- Electric Arc Furnace Slag	Significant	Level 1- Glass Powder	Significant	Level 3- Steel Powder

Main effects plot for means

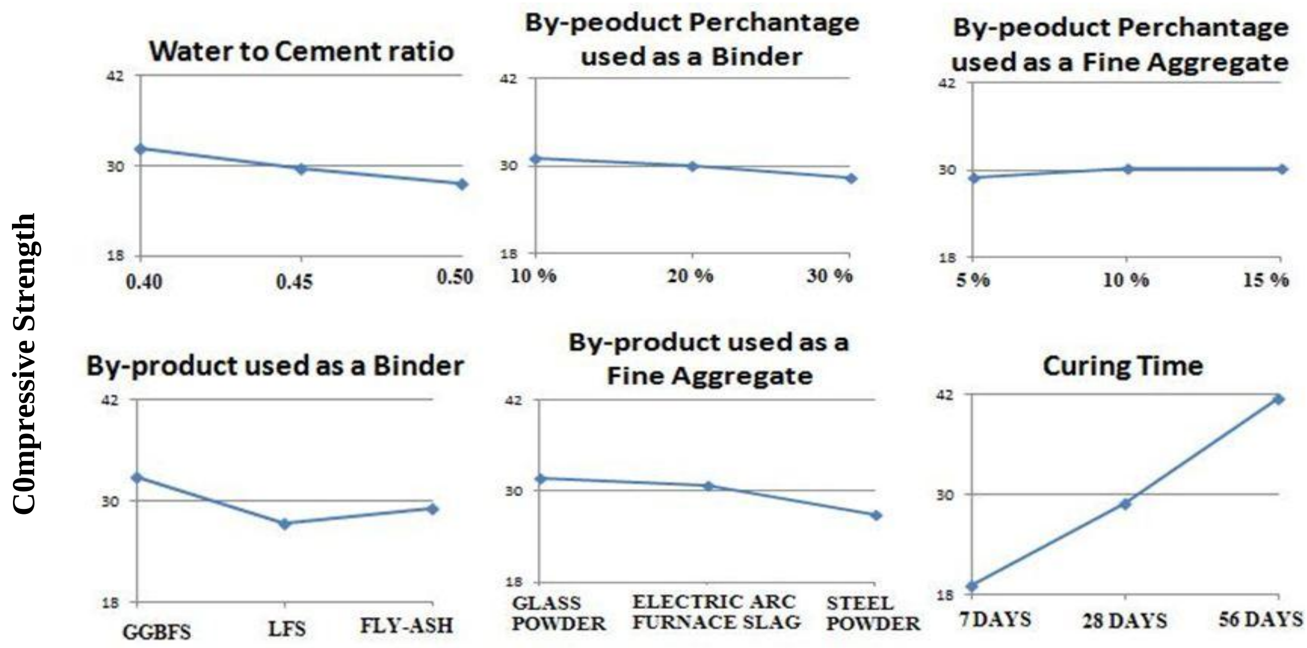
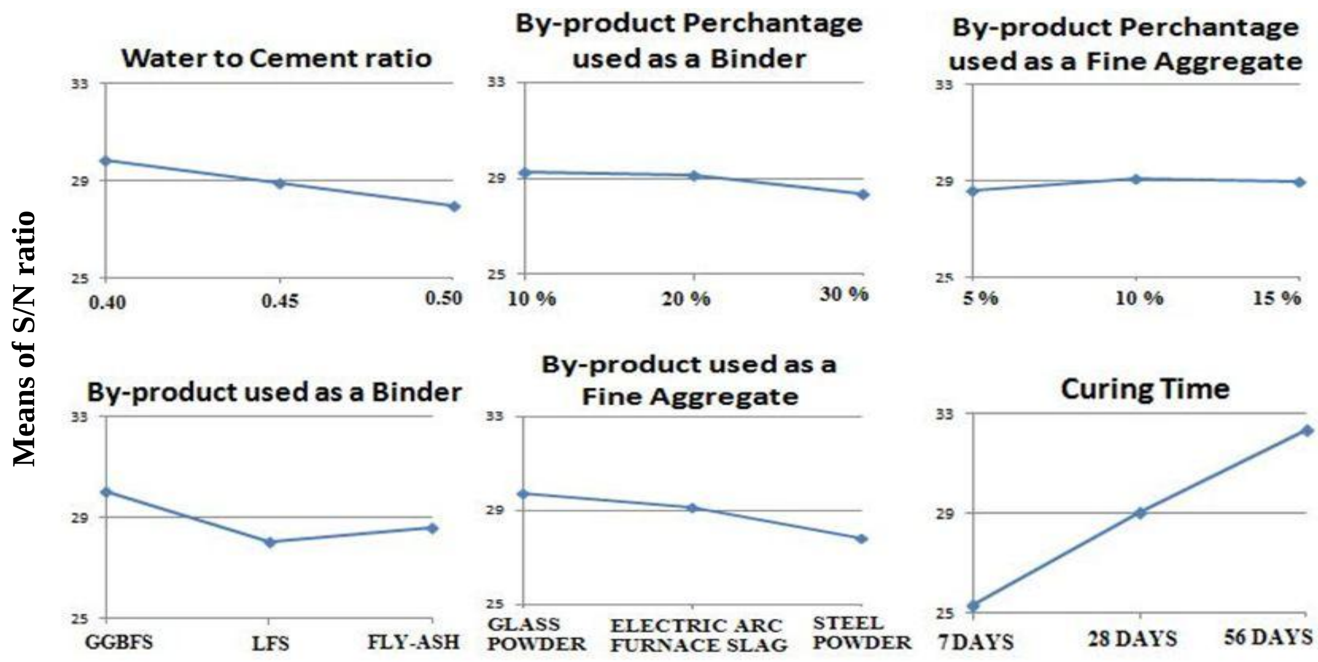


Figure 5.1: Main effects plot for Mean Compressive Strength (Approach -2)

Main effects plot for S/N ratio



S/N ratio = Higher the better

Figure 5.2: Main effects plot for S/N Ratio of Compressive Strength

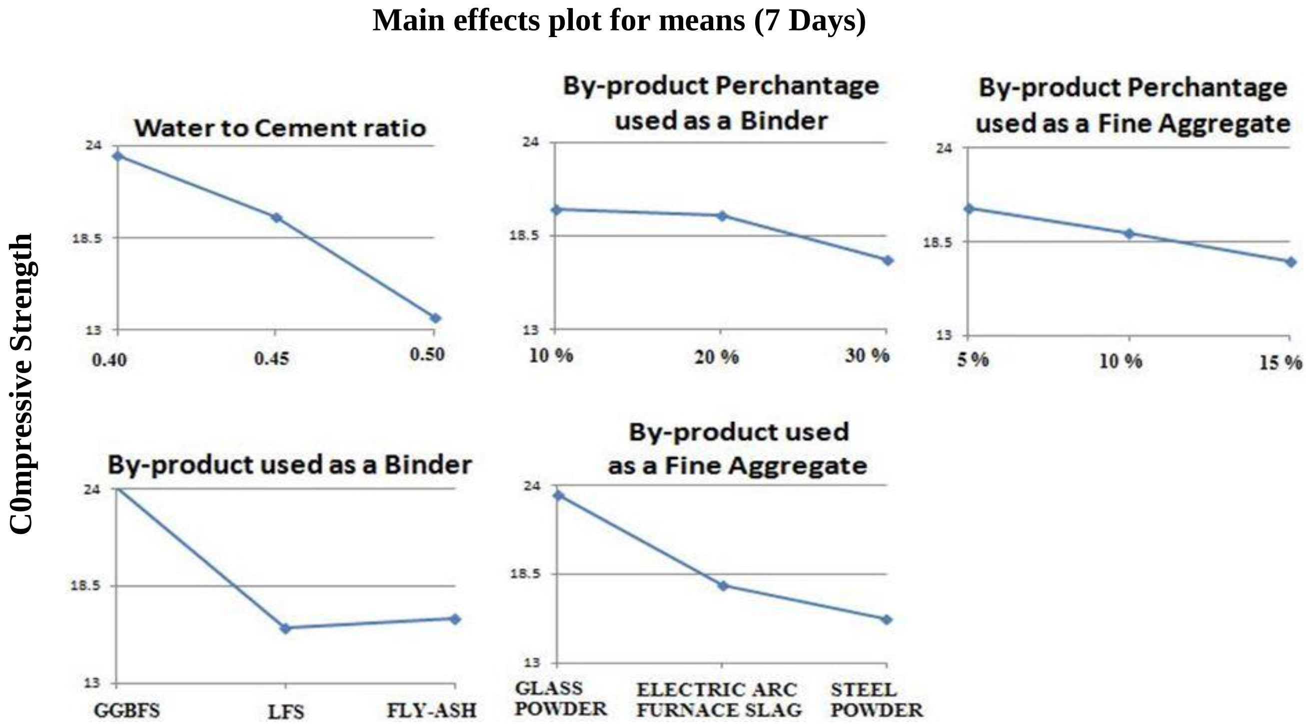


Figure 5.3: Main effects plot for Mean Compressive Strength (7 Days)

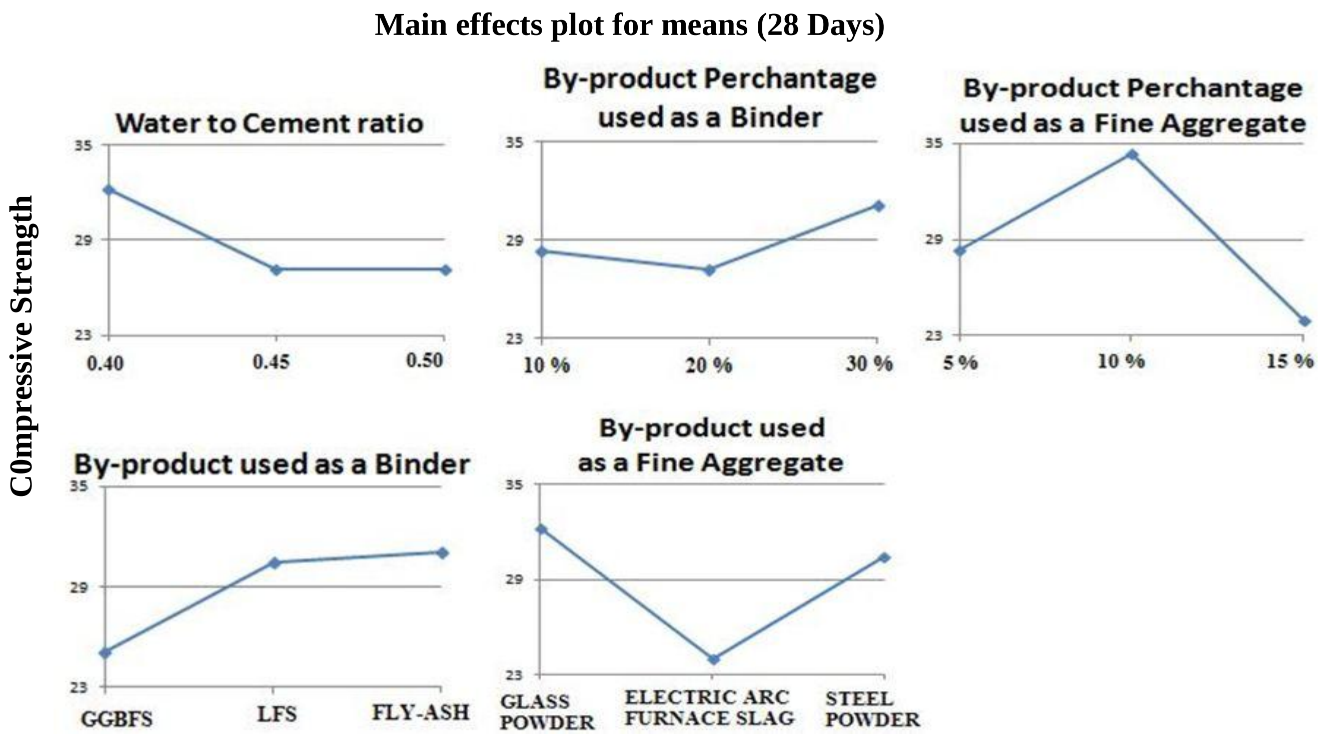


Figure 5.4: Main effects plot for Mean Compressive Strength (28 Days)

Main effects plot for means (56 Days)

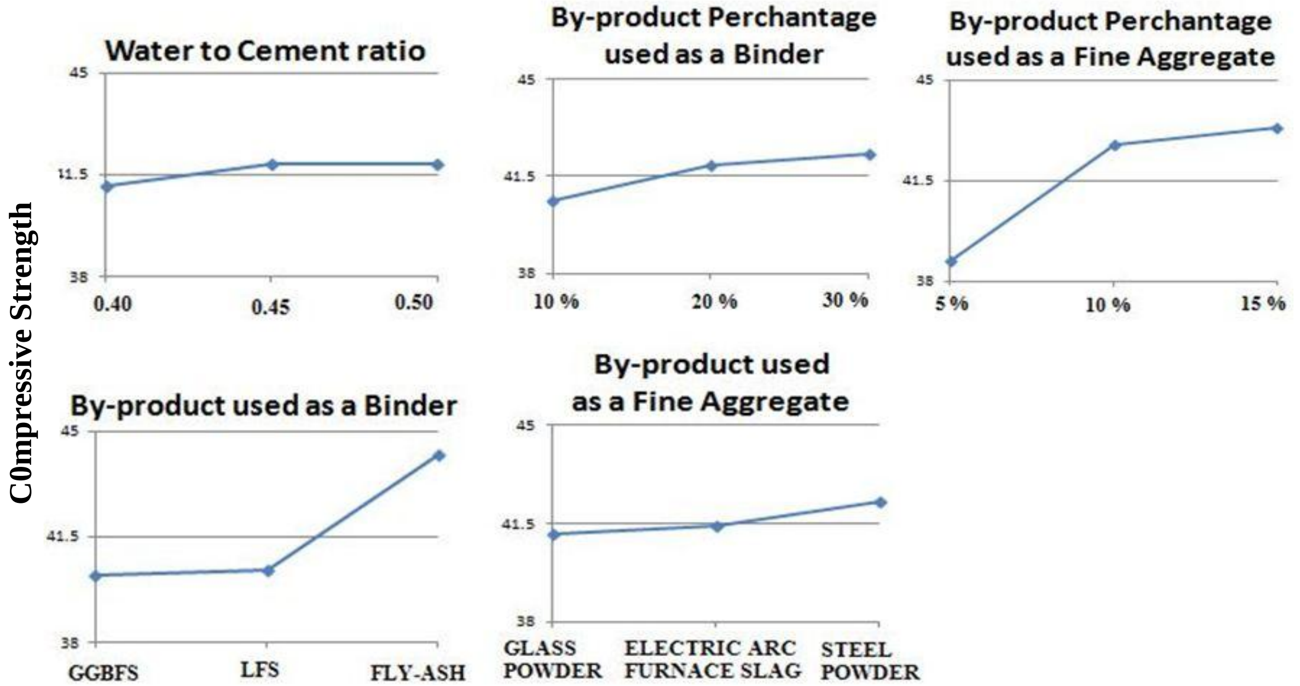


Figure 5.5: Main effects plot for Mean Compressive Strength (56 Days)

Main effects plot for means

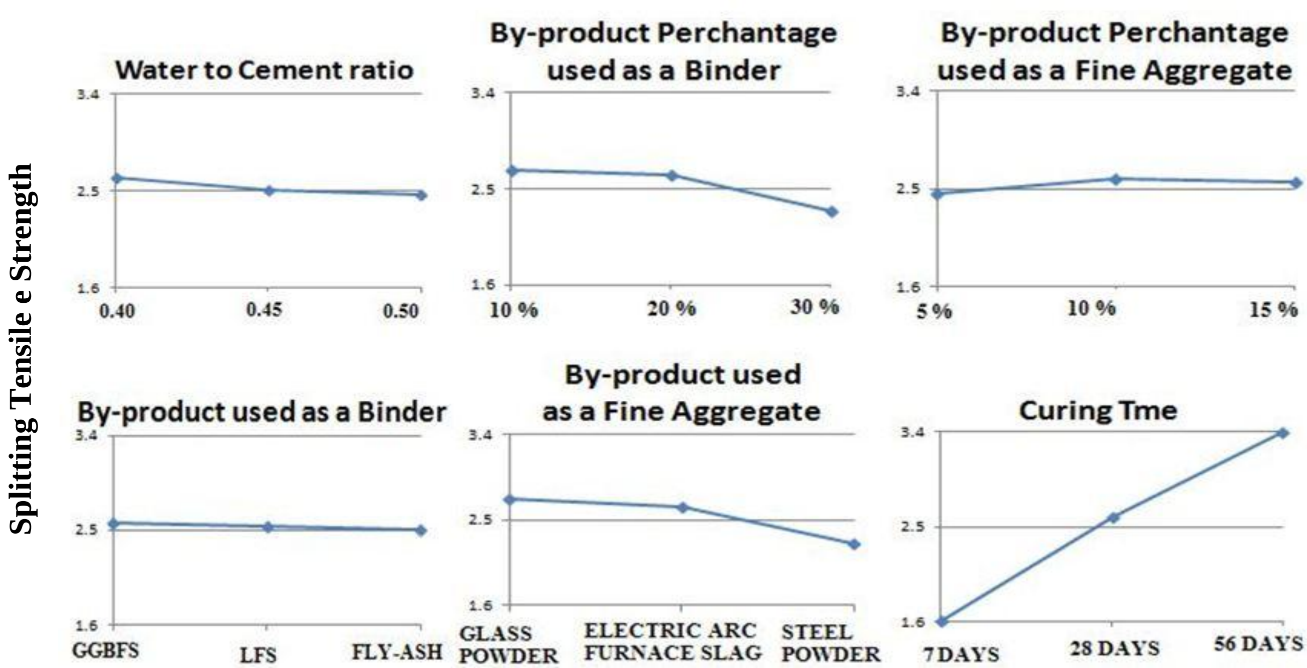
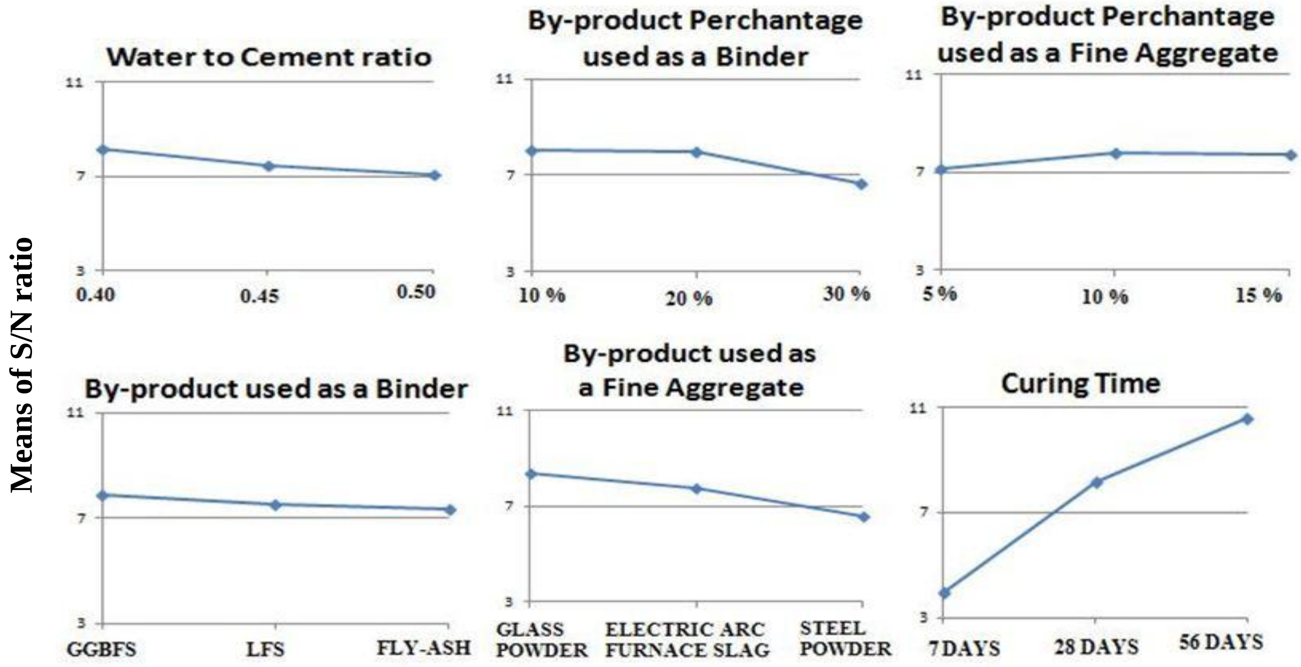


Figure 5.6: Main effects plot for Mean Splitting Tensile Strength

Main effects plot for S/N ratio



S/N ratio = Higher the better

Figure 5.7: Main effects plot for S/N Ratio of Splitting Tensile Strength

Main effects plot for means (7 Days)

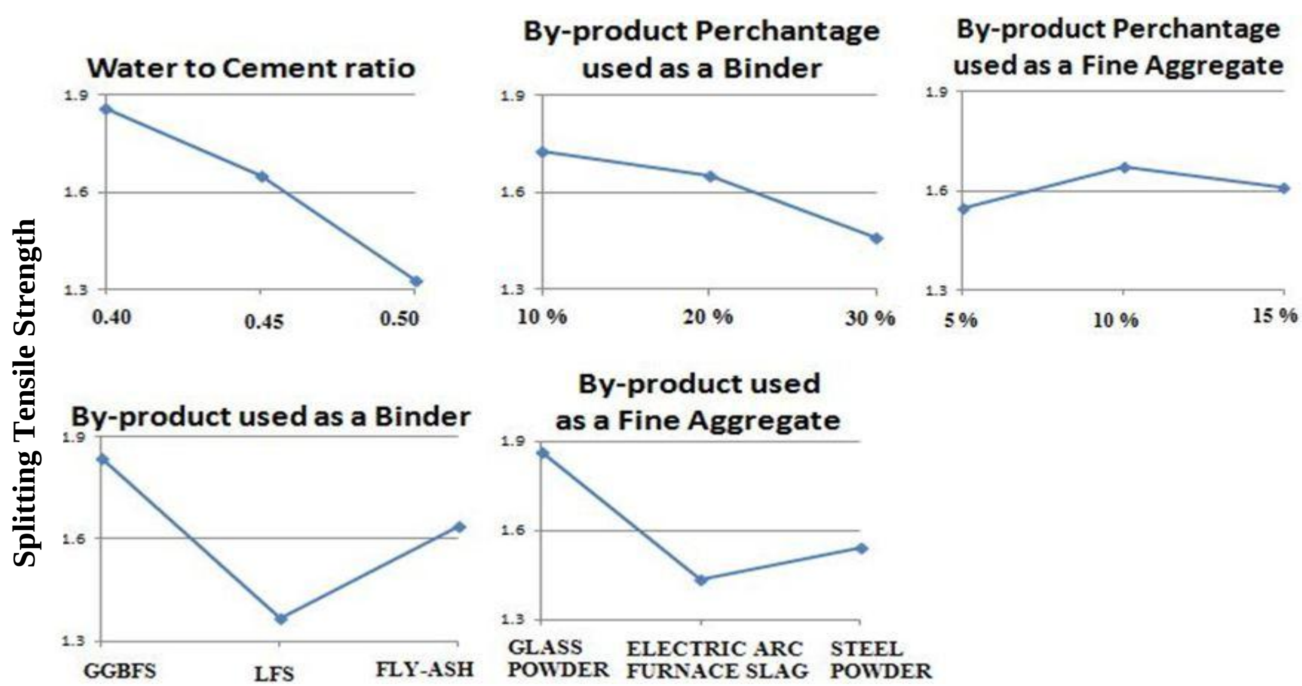


Figure 5.8: Main effects plot for Mean Splitting Tensile Strength (7 Days)

Main effects plot for means (28 Days)

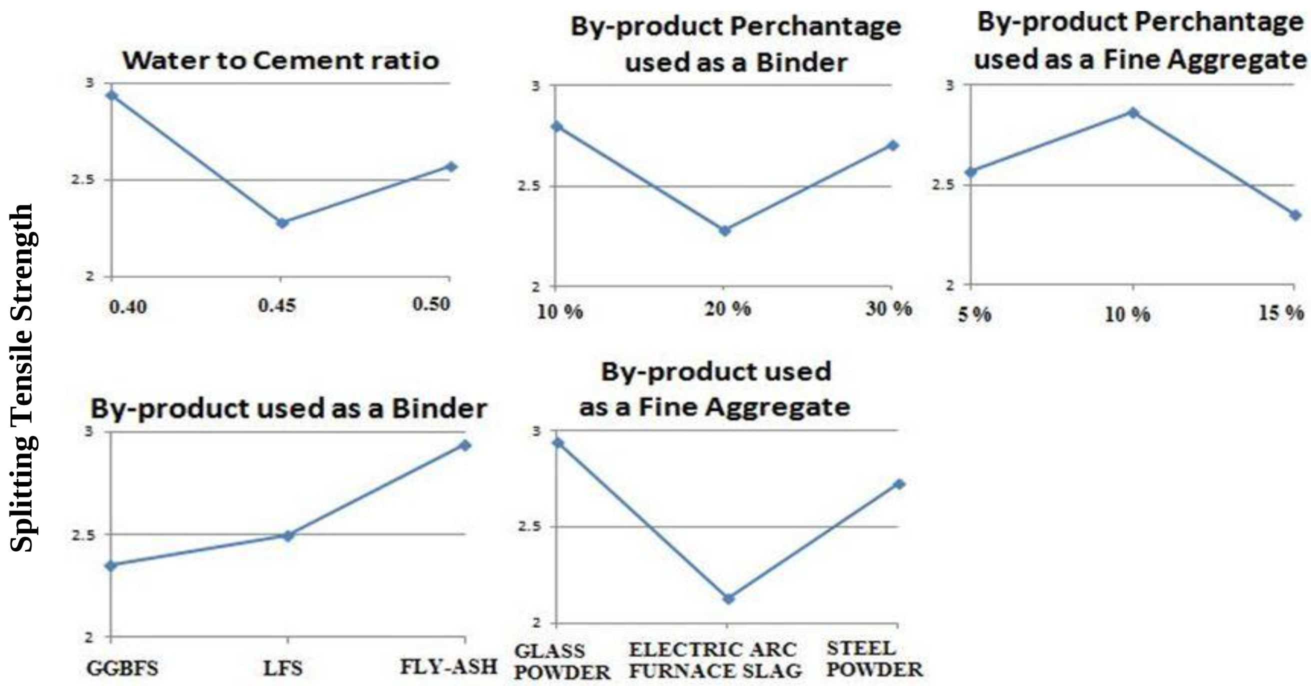


Figure 5.9: Main effects plot for Mean Splitting Tensile Strength (28 Days)

Main effects plot for means (56 Days)

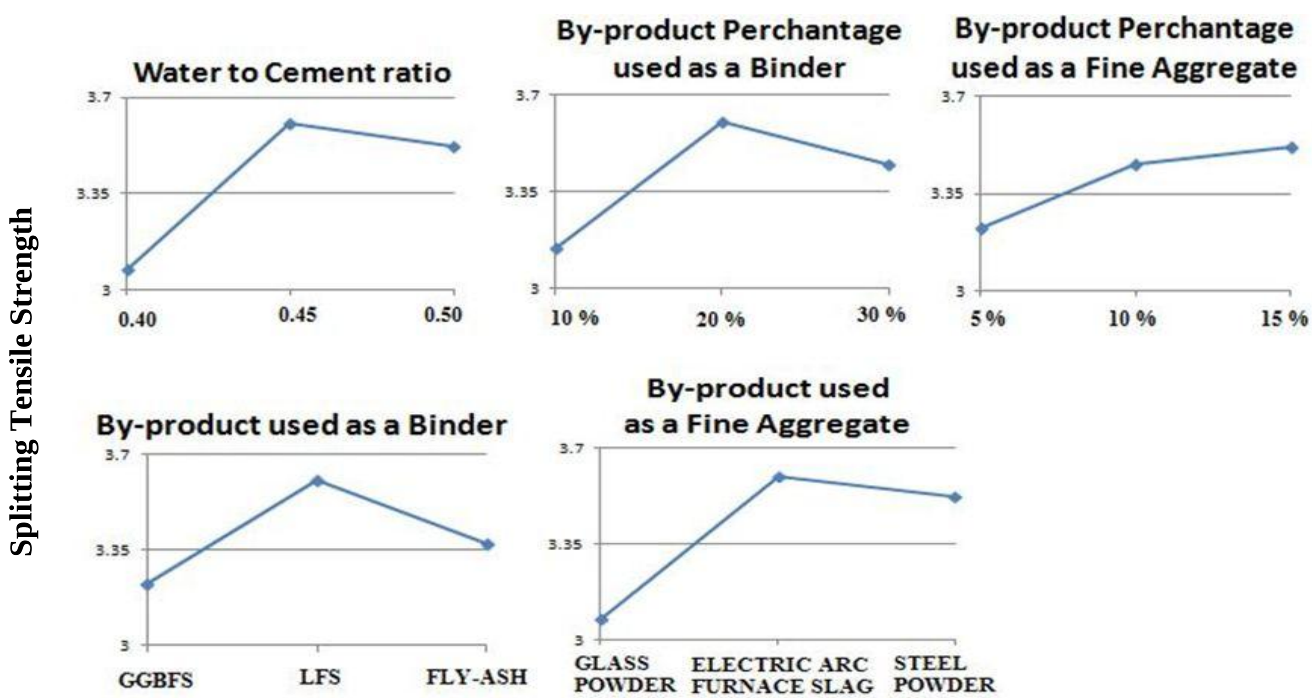


Figure 5.10: Main effects plot for Mean Splitting Tensile Strength (56 Days)

Main effects plot for means

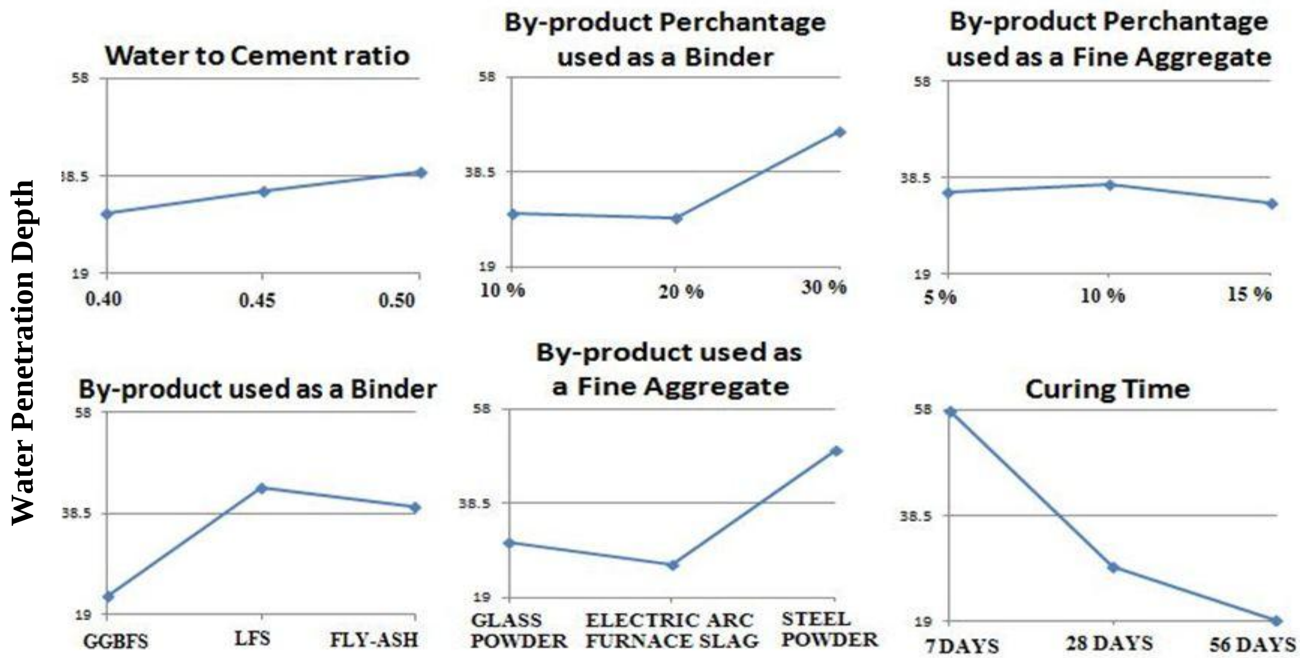


Figure 5.11: Main effects plot for Water Penetration Depth

Main effects plot for means (7 Days)

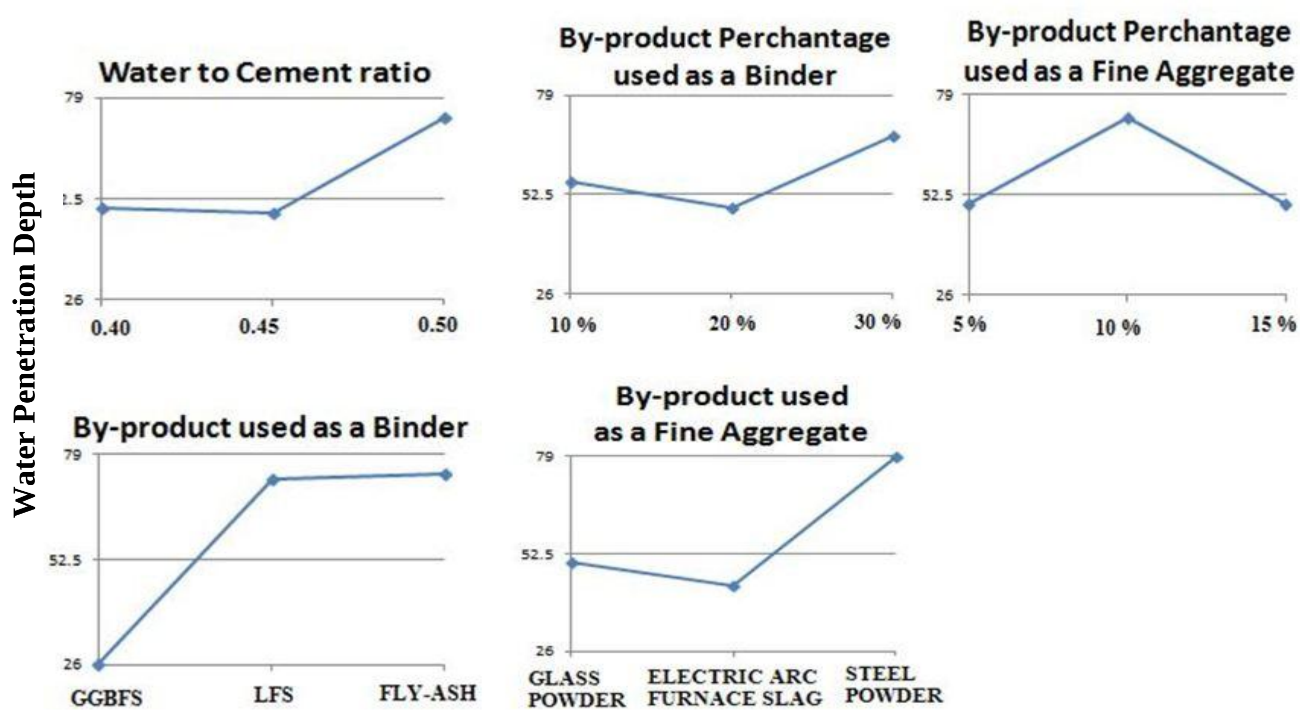


Figure 5.12: Main effects plot for Mean Water Penetration Depth (7 Days)

Main effects plot for means (28 Days)

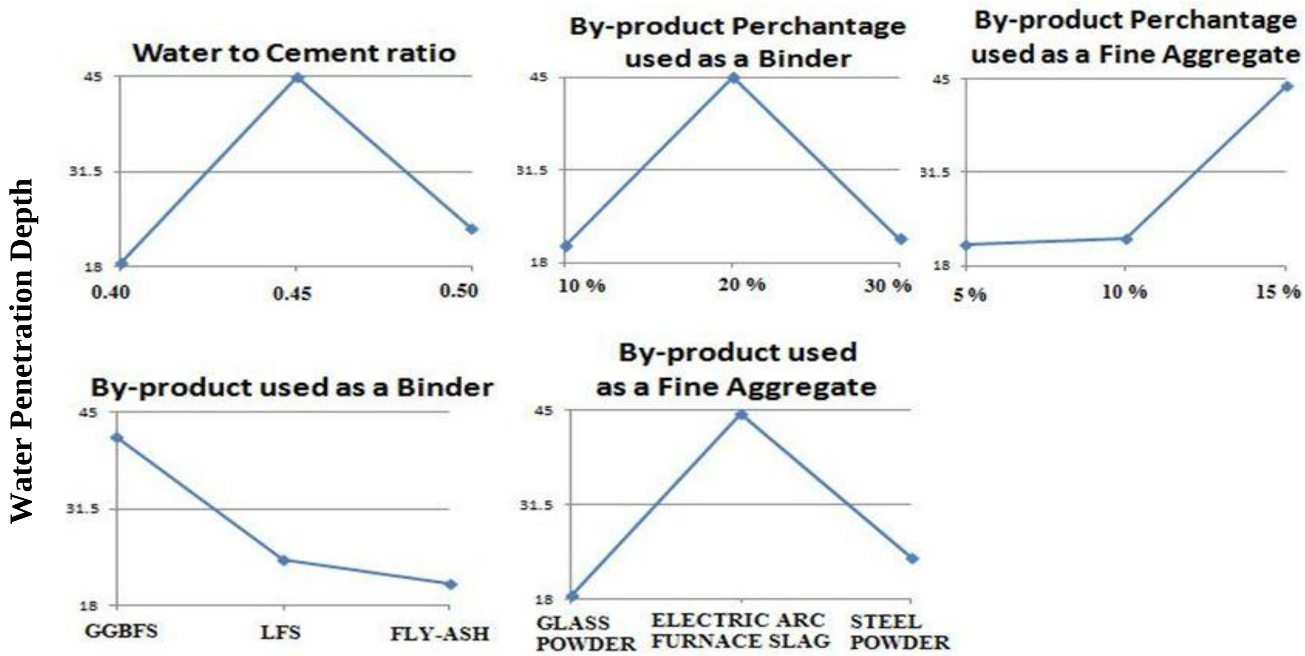


Figure 5.13: Main effects plot for Mean Water Penetration Depth (28 Days)

Main effects plot for means (56 Days)

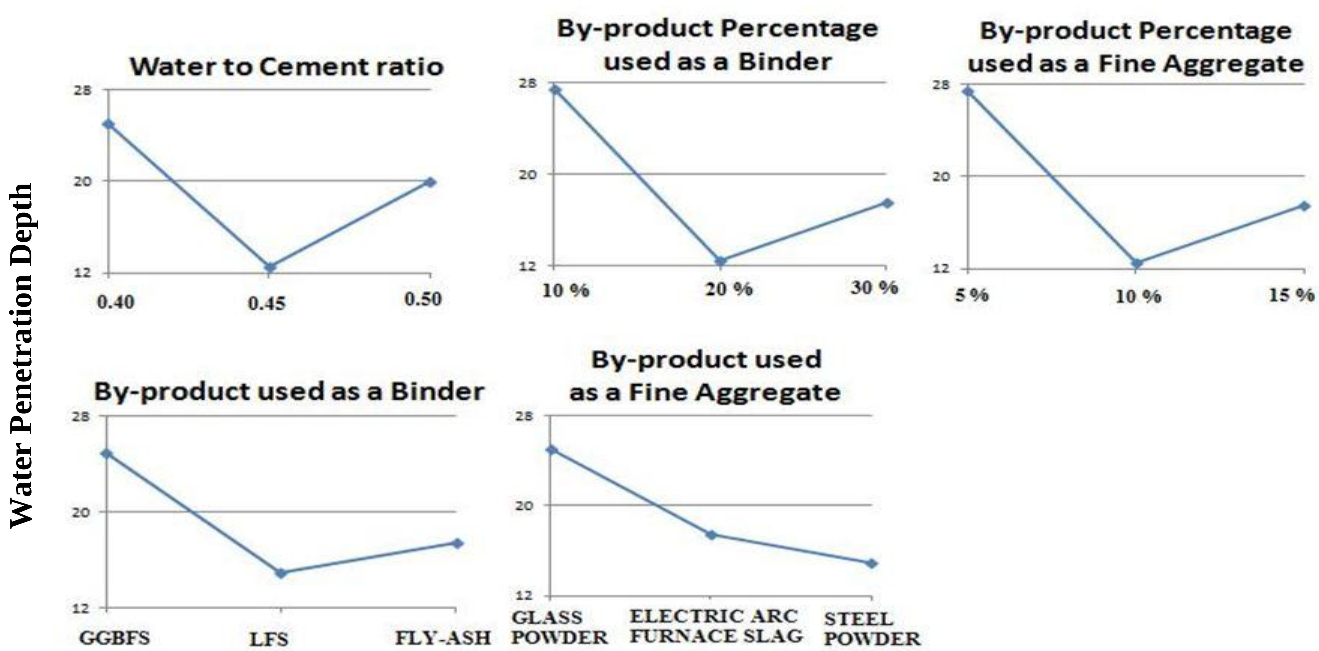


Figure 5.14: Main effects plot for Mean Water Penetration Depth (56 Days)

CHAPTER 6 ANALYSIS OF COMPRESSIVE STRENGTH

6.0 GENERAL

The effect of various parameters such as water to cement ratio, by-product percentage used as a binder, by-product percentage used as a fine-aggregate, type of by-product used as a binder and type of by-product used as a fine-aggregate were evaluated using ANOVA and factorial design analysis for 7 days of curing time. A confidence interval of 95% was used for the analysis. 18 trials were conducted in the experiment using L18 experimental design. Two repetitions for each of 18 trials were completed so as to measure Signal to Noise ratio(S/N ratio).

6.1 Analysis of Variance - Compressive Strength

The results of compressive strength for each of the 18 trails with repetitions for 7 days of curing time are given in Table 6.1. The results were analyzed using ANOVA for identifying the significant factors affecting the performance measures. The Analysis of Variance (ANOVA) for the mean compressive strength at 95% confidence interval is given in Table 6.2. ANOVA table shows that water to cement ratio (F value 19.59) is the factor that significantly affects the compressive strength followed by type of by-product used as a fine-aggregate (F value 11.47), type of by-product used as a binder (F value 10.00) and by-product percentage used as a binder (F value 8.99). By-product percentage used as a fine-aggregate was found to be insignificant. Table 6.3 shows the rank of various factors in the term of their relative significance. Water to cement ratio has the highest rank signifying higher contribution to compressive strength and by-product percentage used as a fine-aggregate has the lowest rank and was observed to be insignificant in affecting compressive strength. Main effect plot for the mean compressive strength is shown in Figure 6.1 Which shows the variation of compressive strength with the input parameters for 7 days curing time.

6.2 Optimal Design consideration

In this experimental analysis, the main effect plot in Figure 6.1 is used to estimate the mean compressive strength for 7 days of curing time with optimal design conditions. In Table 6.6 it is concluded that highest compressive strength was achieve when water to cement ratio 0.45, 10% Ground granulated blast furnace slag as a binder and electric arc furnace slag as a fine aggregate were selected. In S/N ratio highest compressive strength was found when Water to Cement ratio 0.45, ground granulated blast furnace slag(GGBFS) as a binder and electric arc furnace slag as a fine aggregate were selected.

Estimating the mean

Mean value of Compressive Strength for 7 days curing time is given by:

$$\mu_{A2, B1, D1, E2} = \overline{A_2} + \overline{B_1} + \overline{D_1} + \overline{E_2} - 3\overline{T}$$

$$= 23.785+24.19+24.292+23.78 -3(396.21/18)$$

$$= 96.047 – 66.035$$

$$= 30.012 \text{ N/mm}^2$$

Confidence Interval around the Estimating mean

Confidence Interval around the estimated Compressive Strength for 7 days of curing time

$$CI = \sqrt[2]{\frac{F_{\alpha,v1,v2} V_e}{n_{eff}}}$$ Where $F_{\alpha,v1,v2}$ = F ratio

α = risk (0.05)

Confidence = 1-α

v_1 = degree of freedom for mean which is always = 1

v_2 = degree of freedom for error = v_e = 5

$$n_{eff} = \frac{N}{1+dof_{A1,D1,F3}} = \frac{18}{1+(2+2+2+2)} = 2.0$$

Where N = number of trials in the experiment

$$CI = \sqrt[2]{\frac{F_{\alpha,v1,v2} V_e}{n_{eff}}}$$

$$= \sqrt[2]{\frac{6.61*2.74}{2.0}}$$

$$= \pm 3.00 \text{ N/mm}^2$$

Thus the confidence interval around the estimated mean of compressive Strength for 7 days curing time is given by 30.012 ± 3.00 N/mm^2.

6.3 Result for S/N ratio - Compressive Strength

Table 6.4 shows the ANOVA results for S/N ratio of compressive strength at 95% confident interval for 7 days of curing time. Water to cement ratio, type of by-product used as a binder, type of by-product used as a fine aggregate are found to significant. According to F-test water to cement ratio (F value 13.54) was found to be most significant factor affecting the compressive strength followed by type of by-product used as a binder (F value 7.51) and type of by-product used as a fine aggregate (F value 7.48). Main effect plot of S/N ratio for compressive strength for 7 days of curing time are shown in Figure 6.2. Table 6.5 shows the ranks of various factors in the terms of their relative significance. Water to cement ratio has the highest rank which signifies that it provides highest contribution to compressive strength and by-product percentage used as a fine aggregate has the lowest rank and was found to be insignificant in affecting compressive strength.

Table 6.1 Results for Compressive Strength for 7 days curing time (OA)

Trial	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Compressive Strength			Mean	S/N Ratio
						I	II	III		
1	0.40	10%	5	GGBFS	Glass Powder	26.65	27.1	27.2	26.99	28.62
2	0.40	20%	10	FLY-ASH	EAFS	24.5	24.3	23.7	24.2	27.66
3	0.40	30%	15	LFS	Steel Powder	18.02	18.1	18.2	18.11	25.16
4	0.45	10%	5	FLY-ASH	EAFS	24.9	26.95	25.95	25.93	28.26
5	0.45	20%	10	LFS	Steel Powder	21.35	20.46	22.2	21.34	26.56
6	0.45	30%	15	GGBFS	Glass Power	26.13	27.8	26.07	26.7	28.51
7	0.50	10%	10	GGBFS	Steel Powder	20.3	20.15	20.1	20.2	26.09
8	0.50	20%	15	FLY-ASH	Glass Power	16.5	16.6	16.51	16.54	24.36
9	0.50	30%	5	LFS	EAFS	16.91	16.8	16.45	16.72	24.46
10	0.40	10%	15	LFS	EAFS	27.3	28.93	27.04	27.8	28.85
11	0.40	20%	5	GGBFS	Steel Powder	24.13	23.7	23.6	23.81	27.53
12	0.40	30%	10	FLY-ASH	Glass Power	21.27	20.55	20.72	20.85	26.37
13	0.45	10%	10	LFS	Glass Power	27.1	26.92	27.5	27.2	28.68
14	0.45	20%	15	GGBFS	EAFS	23.82	26.08	25.42	25.11	27.97
15	0.45	30%	5	FLY-ASH	Steel Powder	16.66	16.4	16.22	16.43	24.31
16	0.50	10%	15	FLY-ASH	Steel Powder	16.87	17.26	16.92	17.02	24.61
17	0.50	20%	5	LFS	Glass Power	18.6	18.45	17.9	18.32	25.25
18	0.50	30%	10	GGBFS	EAFS	24.12	22.3	22.41	22.94	27.19

Table 6.2 ANOVA for means of Compressive Strength for 7 days curing time

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio(A)	103.40	2	51.70	19.59	5.79	97.92	35.782
By-product as a Binder used (Percent) (B)	47.48	2	23.74	8.99	5.79	42	16.431
By-product as a Fine Aggregate used (Percent) (C)	6.22	2	3.11	1.18	5.79		2.152
By-product used as a Binder(D)	52.83	2	26.42	10.00	5.79	47.35	18.283
By-product used as a Fine Aggregate(E)	60.56	2	30.28	11.47	5.79	55.08	20.956
Error	18.47	7	2.64				6.393
Total	288.97	17					100
e pooled	24.69	9	2.74			46.62	8.545

Table 6.3 Response table for means of Compressive Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	23.627	24.19	21.36	24.29	22.76
2	23.785	21.55	22.78	20.16	23.78
3	18.623	20.29	21.88	21.58	19.48
Delta	5.161	3.89	1.42	4.13	4.29
Rank	1	4	5	3	2

Table 6.4 ANOVA for S/N Ratio of Compressive Strength

Sources	Sum of Squares (SS)	DOF (v)	Variance (V)	Calculated F-Value	F-Critical (95%)	SS'	% Contribution
Water to Cement ratio(A)	16.70	2	8.35	13.54	5.79	14.57	35.58
By-product as a Binder used (Percent) (B)	7.10	2	3.55	5.76	5.79		15.13
By-product as a Fine Aggregate used (Percent) (C)	1.54	2	0.77	1.25	5.79		3.29
By-product used as a Binder(D)	9.26	2	4.63	7.51	5.79	7.13	19.73
By-product used as a Fine Aggregate(E)	9.22	2	4.61	7.48	5.79	7.09	19.66
Error	3.08	7	0.61				6.56
Total	46.92	17					100
e pooled	11.72	11	1.065			18.13	24.98

Table 6.5 Response table for S/N Ratio of Compressive Strength

Level	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate
1	27.367	27.523	26.407	27.655	26.968
2	27.384	26.560	27.097	25.932	27.402
3	25.332	26.001	26.580	26.496	25.714
Delta	2.051	1.521	0.690	1.722	1.688
Rank	1	4	5	2	3

Table 6.6 Significant factors for Compressive Strength

Factors	Affecting mean		Affecting variation (S/N ratio)	
	Contribution	**Best Level**	**Contribution**	**Best Level**
Water to Cement ratio	Significant	Level 2- 0.45	Significant	Level 2- 0.45
By-product as a Binder used (Percent)	Significant	Level 1-10%	Insignificant	-
By-product as a Fine aggregate used (Percent)	Insignificant	-	Insignificant	-
By-product used as a Binder	Significant	Level 1- GGBFS	Significant	Level 1- GGBFS
By-product used as a Fine Aggregate	Significant	Level 2- Electric arc furnace slag	Significant	Level 2- Electric arc furnace slag

Main effects plot for means

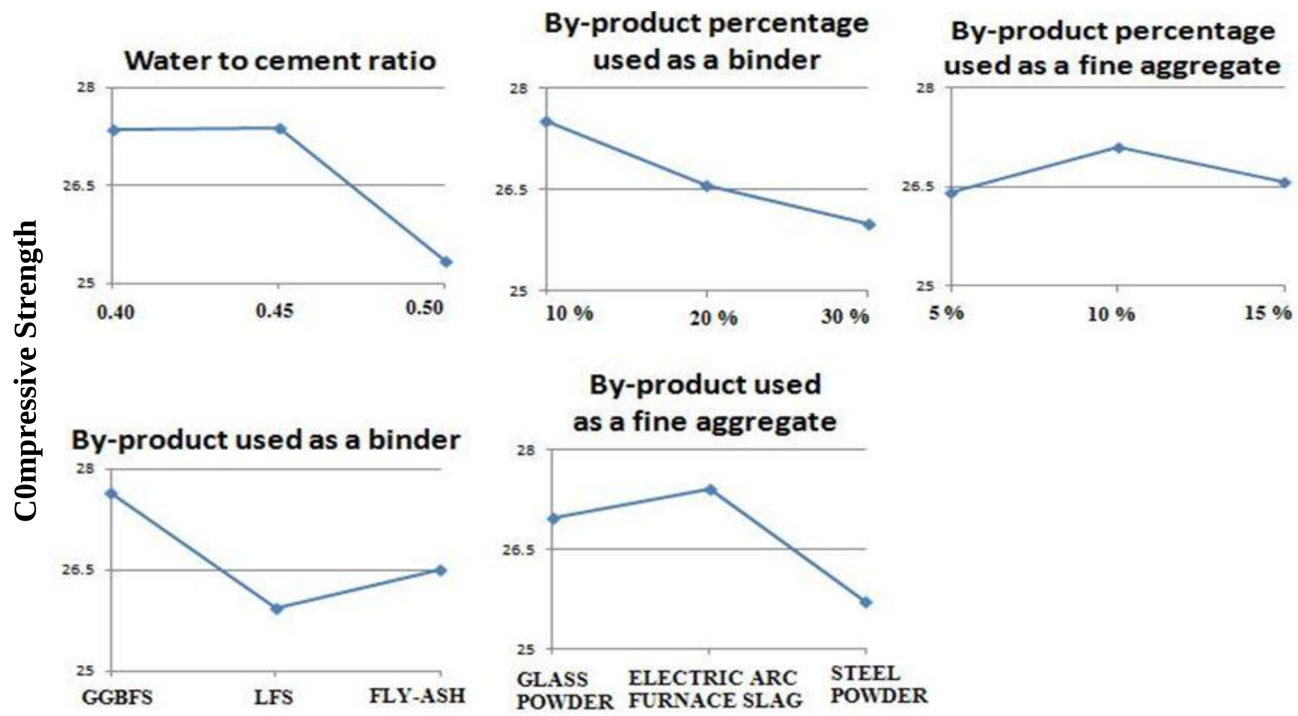
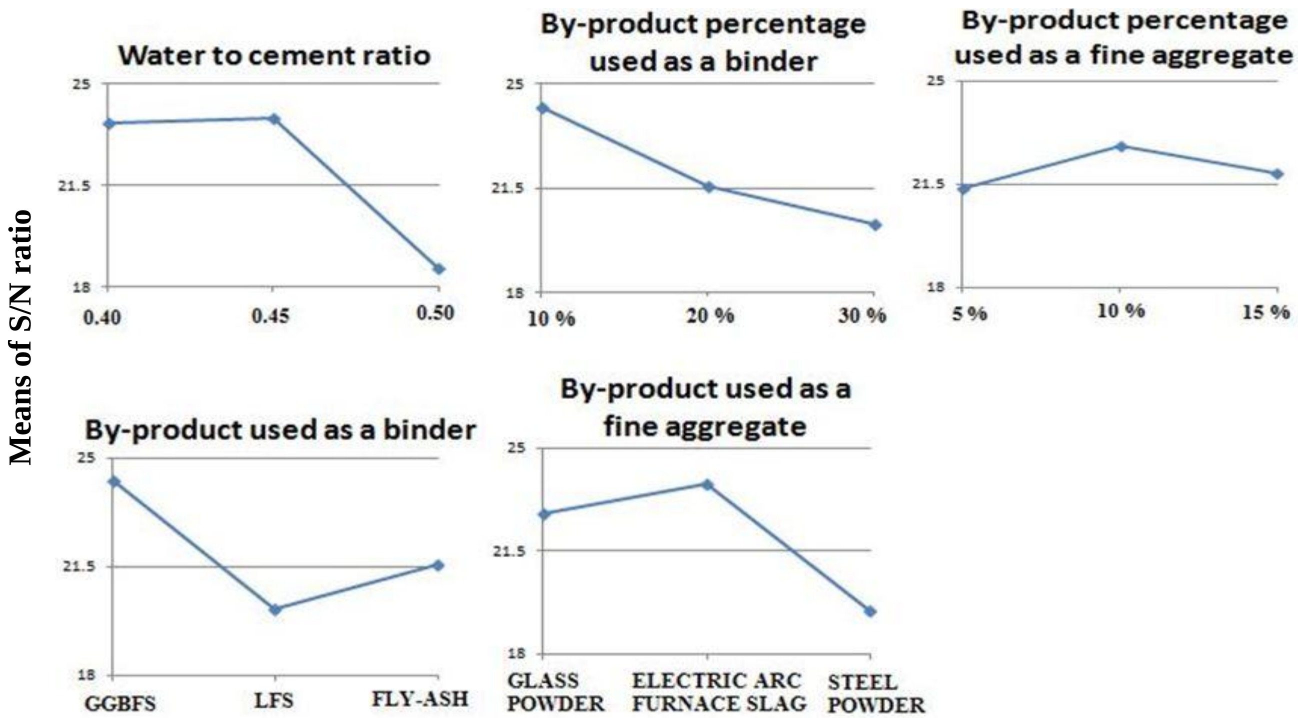


Figure 6.1: Main effects plot for Mean Compressive Strength

Main effects plot for S/N ratio



S/N ratio = Higher the better

Figure 6.2: Main effects plot for S/N Ratio of Compressive Strength

7.1 RESULTS

The effect of various parameters such as water to cement ratio, by-product percentage used as a binder, by-product percentage used as a fine-aggregate, type of by-product used as a binder, type of by-product used as a fine-aggregate and curing time were evaluated using ANOVA and factorial design analysis. The purpose of the ANOVA was to identify the important parameters in prediction of compressive strength, splitting tensile strength and water penetration depth. Results amalgamated from ANOVA and plots are given below. The results are also summarized in Table 6.1, 6.2 and 6.3.

7.1.1 Compressive Strength

Approach -1

- Curing time was found the most significant factor with F value 19.138 and its contribution to compressive strength was 83.46% followed by type of by-product used as a binder (F value 7.786) and water to cement ratio (F value 5.929) were the factors that significantly affect the compressive strength with a contribution of 6.979% and 5.313% respectively. This indicates that other than the curing time and water to cement ratio which as per established norms are the major factors influencing the compressive strength of concrete, type of by-product used as a binder also affects the compressive strength of concrete.
- Other three factors namely by-product percentage used as a binder, by-product percentage used as a fine-aggregate and type of by-product used as a fine-aggregate were found to be insignificant.
- In S/N ratio water to cement ratio, type of by-product used as a binder, type of by-product used as a fine aggregate and curing time are the factors which were found to be significant.
- The estimated mean value of compressive strength when three factors namely curing time (56 days), water to cement ratio (0.40) and by-product used as a

Binder (GGBFS) were considered with 95% confidence interval was found to be 49.231 ± 4.175 N/mm^2.

- A separate analysis was carried out to study the effect of curing time on other parameters for Compressive strength. Highest compressive strength was achieved for 7 days when water to cement ratio 0.40, 20% granulated blast furnace slag as a binder and glass powder as a fine aggregate were selected.
- The highest compressive strength was achieved for 28 days when water to cement ratio 0.40, 30% ladle furnace slag as a binder and 10% glass powder as a fine aggregate were selected.
- For 56 days the highest compressive strength was achieved when water to cement ratio 0.40, 30% fly-ash as a binder and 15% glass powder as a fine aggregate were selected.
- In case of orthogonal design for 7 days of curing time, water to cement ratio was found the most significant factor with F value 19.59 and its contribution to compressive strength was 35.782% followed by type of by-product used as a fine-aggregate (F value 11.47) , type of by-product used as a binder (F value 10.00) and by-product percentage used as a binder (F value 8.99) were the factors that significantly affected the Compressive strength which had contribution to compressive strength were 20.956%, 18.283% and 16.431 respectively.
- By-product percentage used as a fine-aggregate was found to be insignificant.
- In S/N ratio water to cement ratio, type of by-product used as a binder and type of by-product used as a fine aggregate are the factors which were found to be significant.
- The estimated mean value of compressive strength for 7 days of curing time when four factors, namely, water to cement Ratio (0.45), type of by-product used as a Binder (GGBFS), type of by-product used as a fine-aggregate (electric arc furnace slag) and by-product percentage used as a binder (10%) were considered with 95% confidence interval was found to be 30.012 ± 3.00 N/mm^2.

Approach -2

- Curing time was found the most significant factor with F value 150.490 and its contribution to compressive strength was 84.021% followed by type of by-product used as a binder (F value 9.377), type of by-product used as a fine-aggregate (F value 7.663) and water to cement ratio (F value 6.39) were the factors that significantly affected the compressive strength which had contribution to compressive strength was 5.235%, 4.278% and 3.550% respectively.
- Other factors namely by-product percentage used as a binder and by-product percentage used as a fine-aggregate were found to be insignificant.
- In S/N ratio water to cement ratio, type of by-product used as a binder, type of by-product used as a fine aggregate and curing time are the factors which were found to be significant.
- The estimated mean value of compressive strength when four factors namely curing time (56 days), water to cement ratio (0.40), by-product used as a Binder (GGBFS) and by-product used as a fine aggregate (glass powder) were considered with 95% confidence interval was found to be 51.83 ± 4.434 N/mm^2.
- A separate analysis was carried out to study the effect of curing time on other parameters for Compressive strength. Highest compressive strength was achieved for 7 days when water to cement ratio 0.40, 10% granulated blast furnace slag as a binder and 5% glass powder as a fine aggregate were selected.
- The highest compressive strength was achieved for 28 days when water to cement ratio 0.40, 30% Fly-ash as a binder and 10% glass powder as a fine aggregate were selected.
- For 56 days the highest compressive strength was achieved when water to cement ratio 0.40, 30% fly-ash as a binder and 15% Steel powder as a fine aggregate were selected.

7.1.2 Splitting Tensile Strength

Approach -1

- Curing time was found the most significant factor with F value 489.59 and its contribution to splitting tensile strength was 89.216% followed by type of by-product used as a binder (F value 39.091), by-product percentage used as a binder (F value 7.281) and water to cement ratio (F value 5.904) were the factors that significantly affected the Compressive strength which had contribution to splitting tensile strength was 7.123%, 1.326% and 1.075% respectively.
- Other factors namely by-product percentage used as a fine-aggregate and type of by-product used as a fine-aggregate were found to be insignificant.
- In S/N ratio water to cement ratio, type of by-product used as a binder, type of by-product used as a fine aggregate by-product percentage used as a binder and curing time are the factors which were found to be significant.
- The estimated mean value of splitting tensile strength when four factors namely curing time (56 days), water to cement ratio (0.40), by-product used as a Binder (GGBFS) and by-product percentage used as a binder (20%) were considered with 95% confidence interval was found to be 4.155 ± 0.487 N/mm^2.
- A separate analysis was carried out to study the effect of curing time on other parameters for splitting tensile strength. Highest splitting tensile strength was achieved for 7 days when water to cement ratio 0.40, 10% granulated blast furnace slag as a binder and glass powder as a fine aggregate were selected.
- The highest splitting tensile strength was achieved for 28 days when water to cement ratio 0.40, 20% ladle furnace slag as a binder and 5% glass powder as a fine aggregate were selected.
- For 56 days the highest splitting tensile strength was achieved when water to cement ratio 0.40, 30% fly-ash as a binder and 10% by-product as a fine aggregate were selected.

Approach -2

- Curing time was found the most significant factor with F value 113.0 and its contribution to splitting tensile strength was 85.198% followed by by-product used as a fine-aggregate (F value 9.1678) and by-product percentage used as a binder (F value 6.2178) were the factors that significantly affected the splitting tensile strength which had contribution to compressive strength was 6.912% and 4.68% respectively.
- Other factors namely type of by-product used as a binder, water to cement ratio and by-product percentage used as a fine-aggregate were found to be insignificant.
- In S/N ratio by-product percentage used as a fine aggregate and curing time are the factors which were found to be significant.
- The estimated mean value of splitting tensile strength when three factors namely curing time (56 days), by-product percentage used as a Binder (10%) and by-product used as a fine aggregate (glass powder) were considered with 95% confidence interval was found to be 3.74 ± 0.291 N/mm^2.
- A separate analysis was carried out to study the effect of curing time on other parameters for splitting tensile strength. Highest splitting tensile strength was achieved for 7 days when water to cement ratio 0.40, 10% granulated blast furnace slag as a binder and 10% glass powder as a fine aggregate were selected.
- The highest splitting tensile strength was achieved for 28 days when water to cement ratio 0.40, 10% fly-ash as a binder and 10% glass powder as a fine aggregate were selected.
- For 56 days the highest splitting tensile strength was achieved when water to cement ratio 0.40, 10% ladle furnace slag as a binder and 15% Electric arc furnace slag as a fine aggregate were selected.

7.1.3 Water Penetration Depth

Approach -1

- Curing time was found the most significant factor with F value 57.022 and its contribution to water penetration depth was 68.598% followed by by-product percentage used as a binder (F value 8.235), type of by-product used as a fine-aggregate (F value 6.734) and type of by-product used as a binder (F value 6.35) were the factors that significantly affected the water penetration depth which had contribution to water penetration depth were 9.907%, 8.101% and 7.639% respectively.
- Other factors namely water to cement ratio and by-product percentage used as a fine-aggregate were found to be insignificant.
- The estimated mean value of water penetration depth when four factors namely curing time (56 days), by-product percentage used as a binder (10%), by-product used as a fine-aggregate (electric arc furnace slag) and by-product used as a Binder (GGBFS) were considered with 95% confidence interval was found to be 65.220 ± 14.13mm.
- A separate analysis was carried out to study the effect of curing time on other parameters for water penetration depth. Lowest water penetration depth was achieved for 7 days when water to cement ratio 0.40, 10% Granulated blast furnace slag as a binder and 5% Glass powder as a fine aggregate were selected.
- The lowest water penetration depth was achieved for 28 days when water to cement ratio 0.40, 30% Ladle furnace slag as a binder and 5% Glass powder as a fine aggregate were selected.
- For 56 days the lowest water penetration depth was achieved when water to cement ratio 0.40, 20% Ladle furnace slag as a binder and 15% Electric arc furnace slag as a fine aggregate were selected.

Approach -2

- Curing time was found the most significant factor with F value 33.2254 and its contribution to water penetration depth was 48.16% followed by type of by-product used as a fine-aggregate (F value 13.049), type of by-product used as a binder (F value 10.209) and by-product percentage used as a binder (F value 8.336) were the factors that significantly affected the water penetration depth which had contribution to water penetration depth were 18.915%, 14.799% and 12.084% respectively.

- Other factors namely water to cement ratio and by-product percentage used as a fine-aggregate were found to be insignificant.
- The estimated mean value of water penetration depth when four factors namely curing time (56 days), by-product percentage used as a binder (20%), by-product used as a fine-aggregate (electric arc furnace slag) and by-product used as a Binder (GGBFS) were considered with 95% confidence interval was found to be 61.39± 14.87 mm.
- A separate analysis was carried out to study the effect of curing time on other parameters for water penetration depth. Lowest water penetration depth was achieved for 7 days when water to cement ratio 0.45, 20% Granulated blast furnace slag as a binder and 15% Electric arc furnace slag as a fine aggregate were selected.
- The lowest water penetration depth was achieved for 28 days when water to cement ratio 0.40, 10% Fly-ash as a binder and 5% Glass powder as a fine aggregate were selected.
- For 56 days the lowest water penetration depth was achieved when water to cement ratio 0.45, 20% Ladle furnace slag as a binder and 15% Steel powder as a fine aggregate were selected.

7.2 CONCLUSIONS

The following conclusions were drawn from the present study.

- The concrete mixes cast with partial replacement of components by industrial by-products without considering the effect of specific gravities (Approach-1), achieved maximum compressive strength when any percentage of GGBFS as the binder is used. In this case the effects of the by-product used as a fine aggregate and there percentage are insignificant.

- The concrete mixes cast with partial replacement of components by industrial by-product considering the effect of specific gravities (Approach-2), achieved maximum compressive strength when any percentage of GGBFS as a binder and any percentage of glass powder as fine aggregate are used. In this case the effects of the by-product percentage are insignificant.
- Highest splitting tensile strength is achieved when 20% GGBFS as a binder is used in casting of concrete mixes using Approach-1. In this case the effects of the by-product used as a fine aggregate and there percentage are insignificant.
- Highest splitting tensile strength is achieved when 10% by-product as a binder and any percentage of glass powder as a fine aggregate are used using Approach-2. In this case the effects of the by-product percentage are insignificant.
- Lowest water penetration depth is achieved when 10% GGBFS as a binder and any percentage of electric arc furnace slag as a fine aggregate is used with Approach-1. In this case the effects of the by-product percentage are insignificant.
- Lowest water penetration depth is achieved when 20% GGBFS is used as a binder and any percentage of electric arc furnace slag (EAFS) as a fine aggregate are used with Approach-2. In this case the effects of the by-product percentage are insignificant.
- Highest compressive strength is achieved in case of orthogonal design for 7 days of curing time using Approach-1 when 10% GGBFS as a binder and any percentage of electric arc furnace slag as a fine aggregate (EAFS) are used for water to cement Ratio 0.45. In this case the effects of the by-product percentage are insignificant.

7.3 FUTURE SCOPE OF WORK

In this thesis, the use of industrial by-product in concrete mixture to increase compressive strength, splitting tensile strength and durability was studied. This work can be further extended to study

- **Skid resistance**, which is the force developed when a tyre is prevented from rotating along the pavement surface, essential for highway safety. Static shows that 40% of the accidents are due to the poor skid resistance offered by the pavement surface. The thickness of pavement can be reduced, thereby reducing the cost factor, taking into consideration the life of concrete. Based upon this skid resistance the design of vehicle tyres can change in cost effective manner.

- **Fatigue failure**, a phenomenon associated with variable loading or more precisely to cyclic stressing or straining of the pavement surface. Therefore again the thickness of pavement can be reduced, reducing the cost factor, taking into consideration the life of concrete. Therefore, properly constructed and textured concrete pavement will reduce vehicle fuel consumption and design of vehicle tyres.
- **Green highway (Green rating system)** using the industrial by-products Ladle furnace slag, Electric arc furnace slag and Glass powder. The light colored and cool surface of concrete pavement leads to improved visibility, reduce lighting requirement, and reduce heat island effect.

Table 7.1 Summary of Results

Responses	Analysis & Approach	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Curing Time	Estimated Mean Value (µ)
Compressive Strength	ANOVA Approach-1	Significant Level 1-0.40	Insignificant	Insignificant	Significant Level 1-GGBFS	Insignificant	Significant Level 3-56 Days	49.231 ± 4.175 N/mm^2
	ANOVA Approach-2	Significant Level 1-0.40	Insignificant	Insignificant	Significant Level 1-GGBFS	Significant Level 1- Glass Powder	Significant Level 3-56 Days	51.83 ± 4.434 N/mm^2
	S/N Ratio Approach-1	Significant Level 1-0.40	Insignificant	Insignificant	Significant Level 1-GGBFS	Significant Level 1- Glass Powder	Significant Level 3-56 Days	
	S/N Ratio Approach-2	Significant Level 1-0.40	Insignificant	Insignificant	Significant Level 1-GGBFS	Significant Level 1- Glass Powder	Significant Level 3-56 Days	
Splitting Tensile Strength	ANOVA Approach-1	Significant Level 1- 0.40	Significant Level 2-20 %	Insignificant	Significant Level 1-GGBFS	Insignificant	Significant Level 3-56 Days	4.155 ± 0.487 N/mm^2
	ANOVA Approach-2	Insignificant	Significant Level 1-10 %	Insignificant	Insignificant	Significant Level 1- Glass Powder	Significant Level 3-56 Days	3.74 ± 0.291 N/mm^2
	S/N Ratio Approach-1	Significant Level 1- 0.40	Significant Level 2-20 %	Insignificant	Significant Level 1-GGBFS	Significant Level 1- Glass Powder	Significant Level 3-56 Days	
	S/N Ratio Approach-2	Insignificant	Insignificant	Insignificant	Insignificant	Significant Level 1- Glass Powder	Significant Level 3-56 Days	
Water Penetration Depth	ANOVA Approach-1	Insignificant	Significant Level 1-10 %	Insignificant	Significant Level 1GGBFS	Significant Level 2-EAFS	Significant Level 3-56 Days	65.220 ± 14.13 mm
	ANOVA Approach-2	Insignificant	Significant Level 2-20 %	Insignificant	Significant Level 1GGBFS	Significant Level 2-EAFS	Significant Level 3-56 Days	61.39± 14.87 mm

Table 7.2 Summary of Results of 7 days DOE

Responses	Analysis & Approach	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Orthogonal arrays Using 7 Days of Curing Time	Estimated Mean Value (μ)
Compressive Strength	ANOVA Approach-1	Significant Level 2-0.45	Significant Level 1-10 %	Insignificant	Significant Level 1-GGBFS	Significant Level 2-EAFS		30.012 ± 3.00 N/mm^2
	S/N Ratio Approach-1	Significant Level 2-0.45	Insignificant	Insignificant	Significant Level 1-GGBFS	Significant Level 2-EAFS		

Table 7.3 Summary of Results of Curing Time (Separate analysis)

Responses	Analysis & Approach	Water to Cement ratio	By-product as a Binder used (Percent)	By-product as a Fine aggregate used (Percent)	By-product used as a Binder	By-product used as a Fine Aggregate	Separate analysis of Curing Time (Input Parameter)
Compressive Strength	ANOVA Approach-1	Significant Level 1-0.40	Significant Level 2-20 %	Insignificant	Significant Level 1-GGBFS	Significant Level 1- Glass Powder	7 Days
	ANOVA Approach-2	Significant Level 1-0.40	Significant Level 1-10 %	Significant Level 1-5 %	Significant Level 1-GGBFS	Significant Level 1- Glass Powder	
	ANOVA Approach-1	Significant Level 1-0.40	Significant Level 3-30 %	Significant Level 2-10 %	Significant Level 2- LFS	Significant Level 1- Glass Powder	28 Days
	ANOVA Approach-2	Significant Level 1-0.40	Significant Level 3-30 %	Significant Level 2-10 %	Significant Level 3-Fly-ash	Significant Level 1- Glass Powder	
	ANOVA Approach-1	Significant Level 1-0.40	Significant Level 3-30 %	Significant Level 3-15 %	Significant Level 3-Fly-ash	Significant Level 1- Glass Powder	56 Days
	ANOVA Approach-2	Significant Level 1-0.40	Significant Level 3-30 %	Significant Level 3-15 %	Significant Level 3-Fly-ash	Significant Level 3- Steel Powder	
Splitting Tensile Strength	ANOVA Approach-1	Significant Level 1- 0.40	Significant Level 1-10 %	Insignificant	Significant Level 1-GGBFS	Significant Level 1- Glass Powder	7 Days
	ANOVA Approach-2	Significant Level 1- 0.40	Significant Level 1-10 %	Significant Level 2-10 %	Significant Level 1-GGBFS	Significant Level 1- Glass Powder	
	ANOVA Approach-1	Significant Level 1- 0.40	Significant Level 2-20 %	Significant Level 1-5 %	Significant Level 2- LFS	Significant Level 1- Glass Powder	28 Days
	ANOVA Approach-2	Significant Level 1- 0.40	Significant Level 1-10 %	Significant Level 2-10 %	Significant Level 3-Fly-ash	Significant Level 1- Glass Powder	
	ANOVA Approach-1	Significant Level 1- 0.40	Significant Level 3-30 %	Significant Level 2-10 %	Significant Level 3-Fly-ash	Insignificant	
	ANOVA Approach-2	Significant Level 1- 0.40	Significant Level 1-10 %	Significant Level 3-15 %	Significant Level 2- LFS	Significant Level 2-EAFS	56 Days
Water Penetration Depth	ANOVA Approach-1	Significant Level 1- 0.40	Significant Level 1-10 %	Significant Level 1-5 %	Significant Level 1GGBFS	Significant Level 1- Glass Powder	7 Days
	ANOVA Approach-2	Significant Level 2- 0.45	Significant Level 2-20 %	Significant Level 3-15 %	Significant Level 1GGBFS	Significant Level 2-EAFS	
	ANOVA Approach-1	Significant Level 1- 0.40	Significant Level 3-30 %	Significant Level 1-5 %	Significant Level 2- LFS	Significant Level 1- Glass Powder	28 Days
	ANOVA Approach-2	Significant Level 1- 0.40	Significant Level 1-10 %	Significant Level 1-5 %	Significant Level 3-Fly-ash	Significant Level 1- Glass Powder	
	ANOVA Approach-1	Significant Level 2- 0.45	Significant Level 2-20 %	Significant Level 3-15 %	Significant Level 2- LFS	Significant Level 2-EAFS	56 Days
	ANOVA Approach-2	Significant Level 2- 0.45	Significant Level 2-20 %	Significant Level 2-10 %	Significant Level 2- LFS	Significant Level 3- Steel Powder	

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