CONCRETE MIX DESIGN OPTIMIZATION WITH COPPER SLAG AND IRON SLAG AS REPLACEMENT MATERIALS USING TAGUCHI DESIGN OF EXPERIMENTS

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Submitted by

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DECLARATION

I, Arashdeep Singh, hereby declare that this thesis report entitled **"Concrete Mix Design Optimization With Copper Slag And Iron Slag As Replacement Materials Using Taguchi Design Of Experiments"** submitted in the partial fulfilment of the requirements for the award of degree of Master of Engineering in Structural Engineering, in the Civil Engineering Department, Thapar University, Patiala, is wholly my own work. This matter embodied in this report has not been submitted in part or full to any other university or institute for the award of any degree.

Date: 12/7/2017

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CERTIFICATE

This is to certify that above statement made by the student concerned is correct and true to the best of my knowledge & belief.

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And above all, I pay my regards to the **Almighty** for his love and blessings.

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ABSTRACT

Concrete is one of the most widely used material and its demand is increasing day by day. As the production of cement requires high energy usage especially for grinding and calcination of raw materials and it also causes air pollution due to release of high amount of carbon dioxide. The concept of sustainable development should also need to be considered so that natural systems continue to provide natural resources**.** Thus due to these environmental impacts, use of by products have increased. This is also beneficial on economic point of view. Among these there are slags produced in metallic refineries. It is found that most of the slags put no threat to environment and human health. Inclusion of slags in concrete is found to be beneficial in many cases.

The thesis aims to find compressive strength of concrete with partial replacement of cement with copper slag and fine aggregates with iron slag. Taguchi method was used for the analysis of results. ANOVA statistical approach was used to find the effect of change of a parameter on compressive strength of material.

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CHAPTER 1: INTRODUCTION

1.1 GENERAL

Concrete is the most widely used construction material and its demand is increasing day by day. It is mainly used for the construction of high rise buildings, transport networks, water and energy infrastructures. In the present context, the concept of *sustainable development* need to be considered so that the depletion of the natural resources could be stopped, but production of cement is posing several threats to the environment. These include:

- High amount of energy consumed especially for grinding and calcination of raw materials.
- Air pollution caused due to high emission of carbon dioxide.

Thus, due to these environmental impacts, use of by products has increased. This is also beneficial from the economic point of view. Among these readily available materials include slags produced in metallic refineries. It is found that most of the slags serve as excellent cement replacement materials thus reducing the impact on environment.

1.2 SLAG

Slag is a glass-like by-product left over after the desired metal has been separated (i.e., smelted) from its raw ore. Slag is usually a mixture of metal oxides and silicon dioxide. However, slags can contain metal sulfide and elemental metals as well. While slags are generally used to remove waste in metal smelting, they can also serve other purposes, such as assisting in temperature control of the smelting, and 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. Some of the slags which are popularly used as by product/replacement material in concrete are elaborated below:

1.2.1 Copper Slag

Copper slag is a by-product of copper extraction by smelting. According to **Gorai et al., (2003)** the major constituents of a smelting charge are sulphides and oxides of iron and copper. The charge also contains oxides such as Al_2O_3, CaO, MgO and principally SiO_2 which are either present in the original concentrate or added as flux. It is the iron, copper, sulphur, oxygen and these oxides which largely control the chemistry and physical constitution of the smelting system. The first purpose of matte smelting is to ensure sulfidisation of all copper present in the charge so that it enters the matte phase which can be represented as follows:

$$FeS(l) + Cu_2O(l, slag) \leftrightarrow FeO(l, slag) + Cu_2S(l) \qquad \text{--------------------} \ (1)$$

During smelting when silica is added, it combines with the oxides to form strongly bonded silicate anions which group together to form slag phase. The sulphide shows no tendency to form these anion complexes and hence they remain as distinct covalent matte phase, quite dissimilar to the silicate slag. The end product is a solid, hard material.

$$2FeO + 3SiO_2 \rightarrow 2Fe^{2+} + Si_3O_8^{4-} \qquad \text{--------------------} \ (2)$$

To produce every ton of copper, approximately 2.2–3 tons copper slag is generated as a by-product material. Approximately 24.6 million ton of slag is generated from world copper production.

Table 1.1 shows the region wise copper slag generation.

Copper slag is mainly used for surface blast-cleaning. Abrasive blasting is used to clean and shape the surface of metal, stone, concrete and other materials. In this process, a stream of abrasive grains called grit is propelled toward the work piece. Copper slag is just one of many different materials that may be used as abrasive grit. Rate of grit consumption, amount of dust generated, and surface finish quality are some of the variables affected by the choice of grit material.

Table 1.1: Copper slag generation in various regions **(Gorai et al., 2003)**

S. No.	Regions	Copper slag generation/annum in million ton
1	Asia	7.26
2	North America	5.9
3	Europe	5.56
4	South America	4.18
5	Africa	1.23
6	Oceania	0.45

In the construction process, copper slag is generally used for different purposes as laid down below:

- As building blocks, e.g. in construction of houses, bridges etc.
- In embankments and reclaiming low lying areas.
- As an aggregate for the construction of roads.
- In concrete as a partial or full replacement of various components i.e. cement, fine aggregates or coarse aggregates.

Use of copper slag has increased recently as it is not harmful to environment or human health. **Shanmuganathan *et al*. (2008)** carried out toxicity characterization and long term stability studies on copper slag and reported that the slag samples are non-toxic and pose no environmental hazard and additionally poor leachability of the slag metals assure long term stability, even in extreme climates. The tests indicate that the heavy metals present in the slag are stable and are not likely to dissolve significantly even through repetitive leaching under acid rain.

Since copper slag has a low content of CaO, granulated copper slag exhibits pozzolanic properties. As CaO content increases or under the activation of NaOH it can exhibit cementitious properties and can be used as partial or full replacement for Portland cement. Utilization of copper slag for applications such as Portland cement replacement in concrete, and/or as a cement raw material has the dual benefit of eliminating the costs of disposal, and lowering the cost of the concrete.

a) Physical & Mechanical Properties of Copper Slag:

Air-cooled copper slag has a black color and glassy appearance. The specific gravity varies with iron content, from a low of 2.8 to as high as 3.8. The unit weight of copper slag is somewhat higher than that of conventional aggregate. The absorption capacity of the material is typically very low (0.13%). On the other hand, the granulated copper slag is more porous and therefore, has lower specific gravity and higher absorption capacity than air-cooled copper slag. The granulated copper slag is made up of regularly shaped, angular particles, mostly between 4.75 and 0.075 mm. Table 1.2 shows typical physical and chemical properties of a sample of copper slag.

Table 1.2: Typical physical and mechanical properties of copper slag **(Gorai et al., 2003)**

S. No.	Properties of Copper Slag	Results Obtained
1	Appearance	Black, glassy, more vesicular when granulated
2	Unit weight	2800-3800(kg/m^3)
3	Absorption, %	0.13%
4	Bulk Density	23.5-26.5 kN/m^3
5	Conductivity	500 mS/cm
6	Sp. Gravity	2.8-3.8
7	Hardness	6-7 Moh
8	Moisture	<5%
9	Water soluble chloride	<50 ppm
10	Abrasion loss, %	24.1
11	Sodium sulphate soundness loss	0.90%
12	Angle of internal friction	40^o-53^o

The air-cooled and granulated copper slag has a number of favorable mechanical properties for aggregate use, including excellent soundness characteristics, good abrasion resistance, and good stability. It has high friction angle due to sharp angular shape. However, the slag tend to be vitreous or ‘glassy,’ which adversely affects their frictional properties (skid resistance), a potential problem if used in pavement surfaces.

b) Copper Slag characterization:

According to **Moura et al. (2007)** the microscopic observations indicate most of the copper slags are well crystallized. In addition to iron oxides, other oxides such as silica, alumina, lime and magnesia constitute 95% or more of the total oxides. The X-ray diffraction of copper slag results indicate the presence of *fayalite* (Fe_2SiO_4) and *magnetite* (Fe_3O_4). Some high peak frequencies were observed, which suggests a basically crystalline structure. (See figure 1.1)

The particles of copper slag are usually angular in shape as can be seen in figure 1.2, but it can be spherical depending upon the source of copper slag.

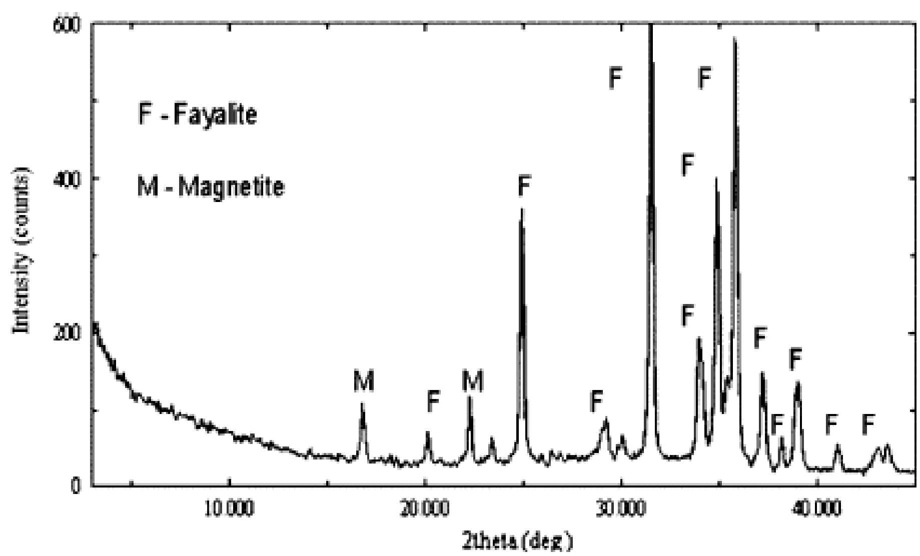

Figure 1.1: X-Ray Diffraction of copper slag (Moura et al., 2007)

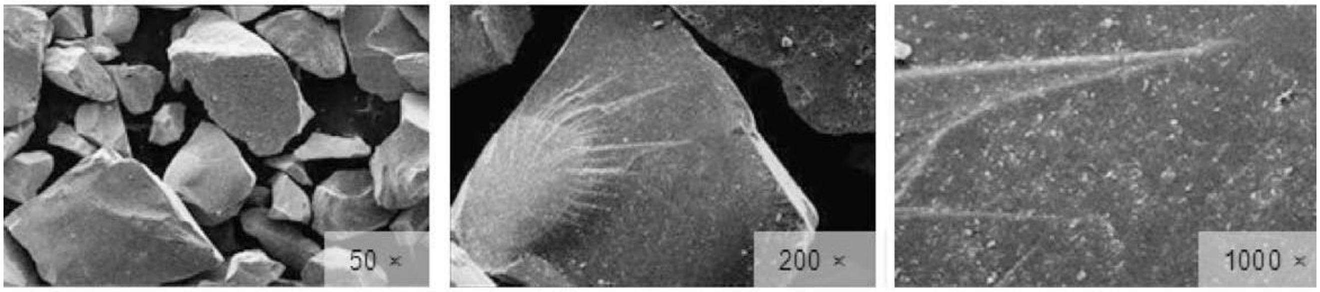

Figure 1.2: SEM micrograph of copper slag (Wu et al., 2010)

1.2.2 Iron Slag

Iron slag refers to the non-metallic molten material created during the production of hot metal and steel. After this material has slowly cooled in the air, it takes the form of artificial crystalline rock. The manner of its formation thus corresponds to that of natural volcanic rocks such as basalts. The iron slag produced in the process can be used in a wide range of applications and is fundamentally different from ash, the residual material from combustion processes.

The history of the use of iron and steel slag dates back a long way. European Slag Association (2006) has reported about the earliest reports on the use of slag, where in it is mentioned that Aristotle used slag as a medicament as early as 350 B.C. All through history use of slag has ranged from the novel to the usual including: cast cannon balls in Germany (1589), wharf buildings in England (1652), slag cement in Germany (1852), slag wool in Wales (1840) armored concrete in Germany (1892) slag bricks made from granulated slag and lime in Japan (1901) according to Iron and Steel (2007). In the past, the application of steel slag was not noticeable because enormous volumes of blast furnace slag were available. Through awareness of environmental considerations and more recently the concept of sustainable development, extensive research and development has transformed slag into modern industrial product which is effective and beneficial.

The American Society of Testing and Materials (ASTM) (1999) defines blast furnace slag as “the non-metallic product consisting essentially of calcium silicates and other bases that is developed in a molten condition at the same time with iron in a blast furnace.” Slag was considered to be essential in the production of iron, but once it served its purpose in refining the metal, it was strictly a nuisance with little or no use. The usefulness of slags was realized with the first ore smelting process. The use of slags became a common practice in Europe at the turn of the 19th century, where the incentive to make all possible use of industrial by-products was strong and storage space for by-products was lacking. Shortly after, many markets for slags opened in Europe, the United States, and elsewhere in the world. Figure 1.3 shows the flow chart of processes of various slags.

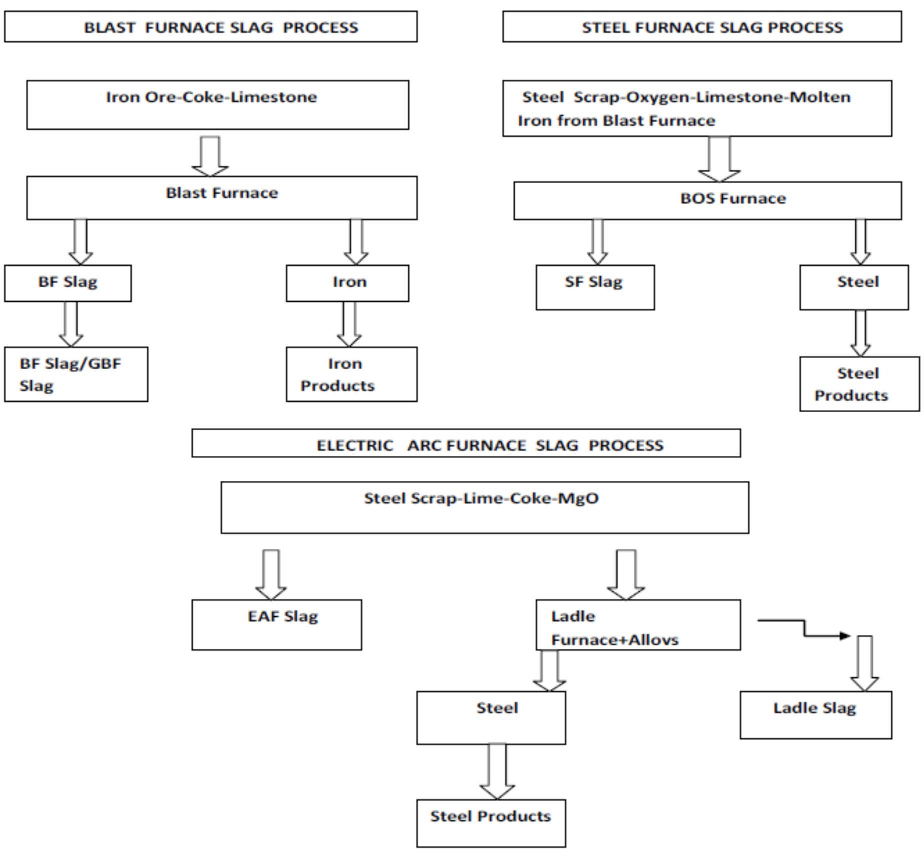

Figure 1.3: Flow chart showing the processes of various slags. **Australasian Slag Association (2002)**

Physical and Mechanical Properties of Iron Slag:

The table 1.3 presents the properties of Iron Slag.

Table 1.3: Chemical composition and physical properties of Iron slag. **(Ouda and Abdel-Gawwad, 2015)**

S. No.	Oxides	BOFS	Physical characteristics	BOFS	Limits for F.A.
1	SiO_2	8.2	Specific gravity	2.71	–
2	Al_2O_3	0.73	Volumetric weight (t/m3)	1.87	–
3	Fe_2O_3	38.89	Clay and fine materials (%)	19.6	64a
4	CaO	39.52			
5	MgO	0.88			
6	SO_3^{2-}	0.24			
7	Cl^-	–			
8	Na_2O	–			
9	K_2O	–			
10	TiO_2	0.22			
11	BaO	0.13			
12	P_2O_5	2.2			
13	L.O.I	0.11			
14	Total	99.96			

1.3 OPTIMIZATION OF CONCRETE MIXES

Optimization of the concrete mixture design is a process of search for a mixture for which the sum of the costs of the ingredients is lowest, yet satisfying the required performance of concrete, such as workability, strength and durability. The basic ingredients of concrete can be classified into two groups: cement paste and aggregates. Although the quality of cement paste is governed mainly by the water/cement ratio, the quantity of cement paste required to achieve a targeted quality of concrete depends on the characteristics of aggregates.

These characteristics mainly include surface area and voids in aggregates. While surface area is governed by the shape and maximum size of aggregates, the void content is affected mainly by the particle size distribution of aggregates. The requirement of the paste can be reduced by reducing the void content of aggregates through proper packing of the aggregates and also by increasing the aggregate/cement ratio.

Goltermann et al. (2007) have suggested a packing model for the aggregate selection and combination to obtain aggregate mixes having the lowest void contents with maximum packing degree (the ratio between bulk density and the aggregate grain density). Thus, the packing degree according to them is a characteristic of the specific aggregate type or mix and it indicates the void volume and the amount of cement paste necessary in the concrete. This indicates that a concrete mixture design can be optimized by adjusting the levels of the key mixture factors such as water to cementitious materials ratio, coarse aggregate to total aggregate ratio, and cementitious material content or aggregate to cementitious materials ratio as reported by various researchers.

1.3.1 Optimization Techniques

There are various optimization techniques which prevalent and are explained as below:

i) Fully experimental methods: These involve an extensive series of tests, sometimes conducted on a trial-and-error basis, and the optimization results are often applicable only to a narrow range of local materials. In order to reduce the number of trial mixtures required to obtain an optimal mixture, efforts have been made towards developing analytical methods rationalizing the initial mixture proportioning into a more logical and systematic process.

ii) Fully analytical methods: These help in searching for an optimum concrete mixture based on detailed knowledge of specific weights of mixture components and on certain basic formulas, which result from previous experience without conducting expensive and time-consuming experimental works.

iii) Semi-experimental (half-analytical) methods: These methods are based on combining the experimental database or experimentally developed prediction models and various analytical tools such as artificial neural network, genetic algorithm, and mathematical programming. Semi-experimental (i.e., half-analytical) methods are reliable and accurate; however, they involve comprehensive laboratory works.

iv) Statistical methods: Statistical methods, also termed as statistical experiment design methods or statistical factorial design methods or design of experiments methods or empirical methods, are an improvement over fully experimental methods, in which, instead of selecting one starting mix proportion and then adjusting by trial and error for achieving the optimum solution, a set of trial batches covering a chosen range of proportions for each mixture component is defined according to established statistical procedures. Trial batches are then carried out, test specimens are fabricated and tested, and experimental results are analyzed using standard statistical methods. These methods include fitting empirical models to the data for each performance criterion. In these models, each response (resultant concrete property) such as strength, slump, or cost is expressed as an algebraic function of factors (individual component proportions) such as w/c, cement content, chemical admixture dosage, and percent pozzolan a replacement.

1.3.2 Design of Experiment

Design of Experiments (DOE) is a powerful statistical technique introduced by R. A. Fisher in England in the 1920. In its broadest sense, Design of Experiments (DOE) has played a major role in the success of the performance of many an enterprise. DOE are methodologies that apply statistics to develop planning of experiments which give a minimum experimental effort to determine the significance level of the results. The DOE assumes that the system is composed of a set of principal variables (or parameters/factors) as inputs and as the response (or results) as the output for each input configuration. The objective is to analyze how the changes in the inputs alter the response. The statistical analysis of the results allows the determination of the significance of the results and to obtain an experimental equation that relates the variables and the results.

1.3.3 Design of Experiment Using Taguchi Method

As a researcher in Electronic Control Laboratory in Japan, **Dr. Genechi Taguchi** carried out significant research with DOE techniques in the late 1940's. He spent considerable effort to make this experimental technique more user-friendly easy to apply and applied it to improve the quality of manufactured products. Dr. Taguchi's standardized version of DOE, popularly known as the Taguchi method or Taguchi approach, was introduced in the USA in the early 1980's. Today it is one of the most effective quality building tools used by engineers in all types of manufacturing activities.

The DOE using Taguchi approach can economically satisfy the needs of problem solving and product/process design optimization projects. According to Taguchi, "quality is the loss imparted to society from the time a product is shipped" (Taguchi and Wu, 1980). In this sense, losses were due to product performance characteristic deviation from targeted value. The effort to minimize deviations of product performance characteristics from an ideal target could be defined as the most important key to quality improvement. Thus, Taguchi sought to minimize deviations from targets by the introduction and use of the loss function. The quadratic loss function (based on Taylor Series approximation) will increase as the quality characteristic deviates on either side of the target (see Figure 1).

It is also systematic about the target. Loss is minimized by producing all items as closed as possible to the target. The old practice of using only the specification limits to determine loss does not hold in practice because a product just stays within the specification rather than a product is right at target. The important point is that the development of loss function results in evaluating costs associated with a deviation from the target and the simplicity of the quadratic loss function results in ease of implementation.

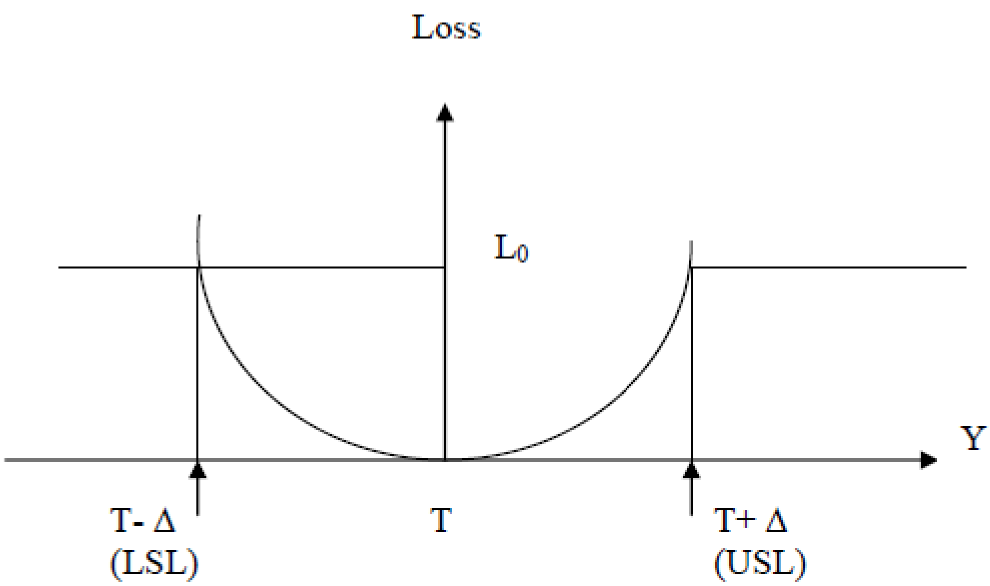

Figure 1.4: Quadratic loss function

An important aspect of the loss function is that it maps deviations from the target into a financial measure. Everyone understands money, and since it is a common measure, comparisons can be made between products and processes. Operationally, the average loss would be computed using a sample large enough to characterize the process measured on a critical quality characteristic.

By learning and applying this technique, engineers, scientists, and researchers can significantly reduce the time required for experimental investigations. The application of DOE requires careful planning, prudent layout of the experiment, and expert analysis of results. Based on years of research and applications Dr. Genechi Taguchi has standardized the methods for each of these DOE application steps. Thus, DOE using Taguchi approach has become a much more attractive tool to practicing engineers and scientists.

1.3.4 Experimentation Approach For Taguchi Method

In the traditional approach of experimentation, while one factor is kept varying, all the other factors are kept constant. If the interactions between the factors are present, the optimum conditions obtained from the conventional approach may not be a true optimum. The number of experiments is numerous for full factorial design, and it is practically not possible to carry out the experiments in most of the cases, primarly due to the expanse and the financial envolved.

To reduce the number of experiments in a research study, several experimental design have been suggested (Roy, 1990). Among several experimental design techniques, the Taguchi method has been successfully applied for a systematic approach to optimize designs and to achieve manufacturing parameters (Roy, 1990: Kackar, 1985: Phadke, 1989: Kim et al., 2003: Yang and Tarng, 1998: Hınıslıoglu and Bayrak, 2004).

One of the advantages of Taguchi method over the conventional experiment design methods, in addition to keeping the experimental cost at the minimum level, is that it minimizes the variability around the target when bringing the performance value to the target value. Another advantage is that optimum working conditions determined from the laboratory work can also be reproduced in the real production environment.

Basically, Taguchi method is a powerful tool for design of quality systems. It provides a simple, efficient and systematic approach to optimize designs for performance, quality and cost (Kackar, 1985).

Therefore the fractional factorial experiments using orthogonal array was investigated by Taguchi variation (Roy, 1990: Kackar, 1985), which can substantially decrease the number of experiments. The linear graph developed by Taguchi (1962) is useful to scientists and engineers to design and analyze the experimental data without having basic knowledge of factorial design.

1.3.5 Taguchi Analytical Design Methodology

The Taguchi method is a powerful tool for the design of a high quality system. It provides a systematic approach to optimize designs for performance and quality. Further, Taguchi parameter design can optimize the performance through the settings of design parameters and reduce the sensitivity of system performance to sources of variation (Roy, 1990: Kackar, 1985).

The use of quantity design in the Taguchi method to optimize a process with one or multiple performance characteristic includes the following steps:

1- Identify the performance characteristic and select process quantities (factors) to be evaluated;
2- Determine the number of quantity levels for the process and possible interaction between the process quantities (factors);
3- Select the appropriate orthogonal array and assignment of the process quantities (factors) to the orthogonal array;
4- Conduct the experiments based on the arrangement of the orthogonal array;
5- Calculate the performance statistic;
6- Analyze the experimental result using the performance characteristic and ANOVA;
7- Select the optimal levels of process quantities (factors);
8- Verify the optimal process quantities (factors) through the confirmation experiment.

1.4 SCOPE OF PRESENT WORK

In the present work, copper slag is used as a partial replacement of cement and iron slag is used as partial replacement of sand. Copper slag was replaced with cement by percentages of 15%, 25% and 35% and Iron Slag was replaced with Sand in percentages of 10%, 20% and 30%. Three different w/b ratios were selected as 0.4, 0.44, and 0.48. Each sample was cured for time periods of 7 and 28 days. 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. Taguchi analytical approach was used to analyze the obtained values.

1.5 OBJECTIVES OF THE WORK

Following are the different objectives of the work:

1) Finding the optimum quantity of copper slag replacement with cement so as to achieve optimum compressive strength.

2) Finding the optimum quantity of iron slag replacement with cement so as to achieve optimum compressive strength.

3) Finding the optimum water to binder ratio for achieving maximum compressive strength.

4) Funding the significance of different parameters in compressive strength variation.

CHAPTER 2: LITERATURE REVIEW

2.0 GENERAL

Many researchers have incorporated Copper Slag as well as Iron Slag in concrete as partial replacement materials. Some researchers have also worked on optimally designing concrete mixes which use supplementary cementing materials. Some of the works carried out in the above areas are presented in the succeeding sections.

2.1 USE OF COPPER SLAG AS PARTIAL REPLACEMENT MATERIAL

Al-Jabri et al. (2006) [1]

The research was undertaken to study the effect of copper slag and cement by-pass dust addition on concrete properties. In addition to the control mixture, two different trial mixtures were prepared using different proportions of copper slag and cement by-pass dust. Cement by-pass dust was primarily used as an activator. One mixture consisted of 5% copper slag substitution for portland cement. The other mixture consisted of 13.5% copper slag, 1.5% cement by-pass dust and 85% portland cement. Three water-to-binder (w/b) ratios were studied: 0.5, 0.6 and 0.7. Concrete cubes, cylinders and prisms were prepared and tested for strength after 7 and 28 days of curing. The modulus of elasticity of these mixtures was also evaluated. Results showed that 5% copper slag substitution for portland cement gave a similar strength performance as the control mixture, especially at w/b ratios of 0.5 and 0.6. Higher copper slag (13.5%) replacement yielded lower strength values. Results also demonstrated that the use of copper slag and cement by-pass dust as partial replacements of portland cement has no significant effect on the modulus of elasticity of concrete, especially at small quantities substitution. See figure 2.1

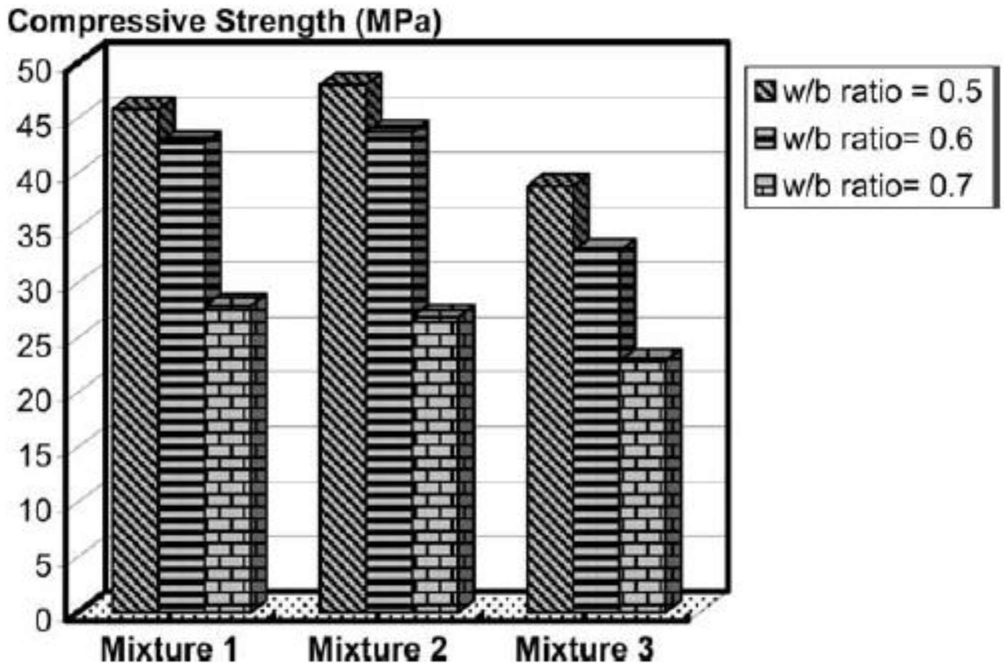

Figure 2.1: 28-Day cube average compressive strength for different mixtures and water-to-binder ratios.

Al-Jabri et al. (2009) [2]

This research study was conducted to investigate the performance of high strength concrete (HSC) made with copper slag as partial replacement of fine aggregate at constant workability and to study the effect of superplasticizer addition on the properties of HSC made with copper slag. Two series of concrete mixtures were prepared with different proportions of copper slag. The first series consisted of six concrete mixtures prepared with different proportions of copper slag at constant workability. The water content was adjusted in each mixture in order to achieve the same workability as that for the control mixture. Twelve concrete mixtures were prepared in the second series. Only the first mixture was prepared using superplasticizer whereas the other eleven mixtures were prepared without using superplasticizer and with different proportions of copper slag used as sand replacement. The results indicated that the water demand reduced by almost 22% at 100% copper slag replacement compared to the control mixture. The strength and durability of HSC generally improved with the increase of copper slag content in the concrete mixture. However, the strength and durability characteristics of HSC were adversely affected by the absence of the superplasticizer from the concrete paste despite the improvement in the concrete strength with the increase of copper content. All concrete mixtures did not meet the strength and durability design requirements due to the segregation and dryness of the concrete paste. Therefore, it was be concluded that the use of copper slag as sand substitution improves HSC strength and durability characteristics at same workability while superplasticizer is very important ingredient in HSC made with copper slag in order to provide good workability and better consistency for the concrete matrix.

Alnuaimi (2012) [4]

Use of copper slag (CS) as a replacement for fine aggregate (FA) in RC slender columns was experimentally investigated in this study. Twenty columns measuring 150 mm x150 mm x 2500 mm were tested for monotonic axial compression load until failure. The concrete mixture included ordinary Portland cement (OPC) cement, fine aggregate, 10 mm coarse aggregate, and CS. The percentage of cement, water and coarse aggregate were kept constant within the mixture, while the percentage of CS as a replacement for fine aggregate varied from 0 to 100%.

Four 8 mm diameter high yield steel and 6 mm mild steel bars were used as longitudinal and transverse reinforcement, respectively. Five cubes measuring 100 mm x100 mm x100 mm, eight cylinders measuring 150 mm x 300 mm and five prisms measuring 100 mm x 100 mm x 500 mm were cast and tested for each mixture to determine the compressive and tensile strengths of the concrete. The results showed that the replacement of up to 40% of the fine aggregate with CS caused no major changes in concrete strength, column failure load, or measured flexural stiffness (EI). Further increasing the percentage reduced the concrete strength, column failure load, and flexural stiffness (EI), and increased concrete slump and lateral and vertical deflections of the column. The maximum difference in concrete strength between the mixes of 0% CS and 100% CS was 29%, with the difference between the measured/ control failure loads between the columns with 0 and 100% CS was 20% the maximum difference in the measured

EI between the columns with 0 and 100% CS was 25%. The measured to calculate failure loads of all specimens varied between 91 and -100.02%. The measured steel strains were proportional to the failure loads. It was noted that columns with high percentages of CS (≥60%) experienced buckling at earlier stages of loading than those with lower percentages of CS.

Ambily et al. (2015) [5]

This paper investigated the technical feasibility of using copper slag as fine aggregate replacement in ultra high performance concrete (UHPC). The studies demonstrated that it is possible to produce UHPC having compressive strength greater than 150 MPa by incorporation of copper slag. The complete replacement of standard sand by copper slag resulted in a maximum decrease in 28-day compressive strength of about 15–25% whereas, the flexural strength, fracture energy recorded was of the similar order.

Chithra et al. (2016) [7]

Multiple Regression Analysis (MRA) and Artificial Neural Network (ANN) models were constructed to predict the compressive strength of High Performance Concrete containing nano silica and copper slag as partial cement and fine aggregate replacement respectively. The data used in the model construction were obtained from laboratory experiments. The compressive strength was experimentally determined for specimens containing 0%, 0.5%, 1%, 1.5%, 2%, 2.5% and 3% of nano silica as partial cement replacement as well as 0%, 10%, 20%, 30%, 40% and 50% of copper slag as partial fine aggregate replacement at curing ages of 1, 3, 7, 28, 56 and 90 days, accounting for a total of 264 observations. The observations were grouped into three sets based on the mineral admixtures incorporated. The mix constituents were fed as the input parameters to achieve the compressive strength as the target. The three sets of data were modeled using both Multiple Regression Analysis and Artificial Neural Networks and their results were evaluated and compared. Artificial Neural Network models demonstrated more accuracy and had higher correlation.

Edwin et al. (2015) [9]

This research investigated the use of copper slag as supplementary cementitious materials (SCM) in ultra high performance mortar (UHPM). Two secondary slag types were utilized as supplementary cementitious materials and were classified as a quickly cooled granulated copper slag (QCS) and a slowly cooled broken copper slag (SCS). Both materials were ground intensively using a planetary ball mill. A low water-to-binder ratio of 0.15 was chosen for the UHPM in this study. Various mortar and cement paste samples were produced with copper slag content from 0 to 20 wt% in steps of 5 wt%.

Before using the copper slag as SCM, both QCS and SCS were intensively ground using a planetary ball mill. A short duration (3 times during 4 minutes at 300 rpm) (SCS I; QCS I) and long duration (5 times during 12 minutes at 300 rpm) (SCS II; QCS II) were chosen in order to obtain two levels of fineness to assess the effect of fineness on the reactivity of the copper slag.

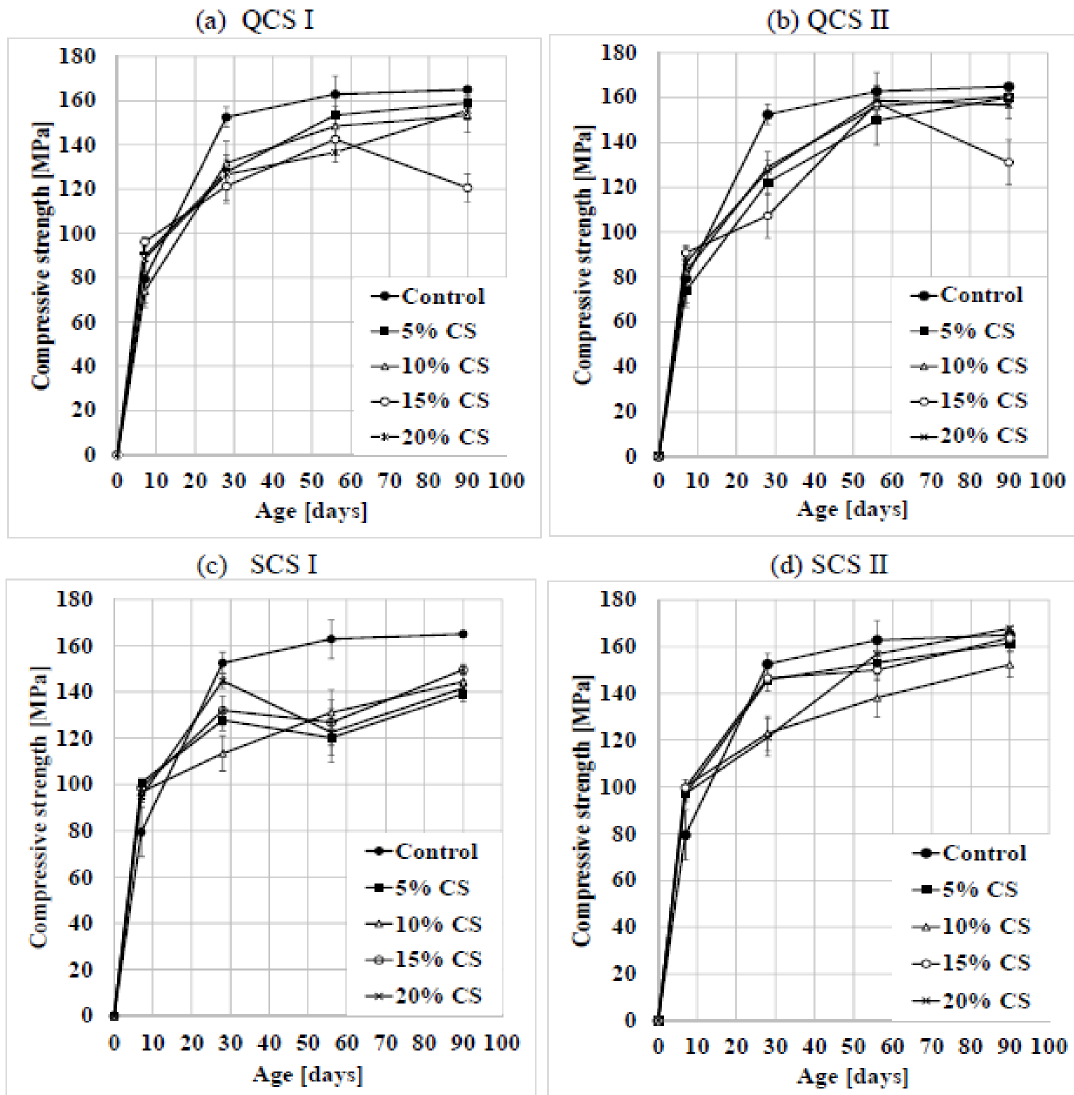

Figure 2.2: Mortar compressive strength results (**Edwin et al., 2015**)

Edwin et al. (2016) [10]

Similar to previous experiment, they investigated the use of copper slag as supplementary cementitious material (SCM) in ultra high performance mortar (UHPM). Two secondary slag types were utilized as SCM and were classified as a quickly cooled granulated copper slag (QCS) and a slowly cooled broken copper slag (SCS). Both materials were ground intensively using a planetary ball mill. A low water-to-binder ratio of 0.15 was chosen for the UHPM in this study. Various mortar and cement paste samples were produced with increasing copper slag content from 0 to 20 wt% in steps of 5 wt%. Particle size distribution (PSD) and specific surface area (SSA) of the copper slag were assessed using laser diffraction and the Blaine permeability test. The pozzolanic activity of copper slag was evaluated using the Chapelle test, strength activity index (SAI) and Frattini test.

The results obtained, showed that the strength of mortars with different copper slag proportions was comparable to or even better than the control mixture at 90 days. The increased fineness of the copper slag enhances the mortar strength. Using isothermal calorimetry, it was found that the addition of copper slag slows down the hydration of the cement pastes. The rate of pozzolanic activity of copper slag depends on temperature, curing age, and particle sizes.

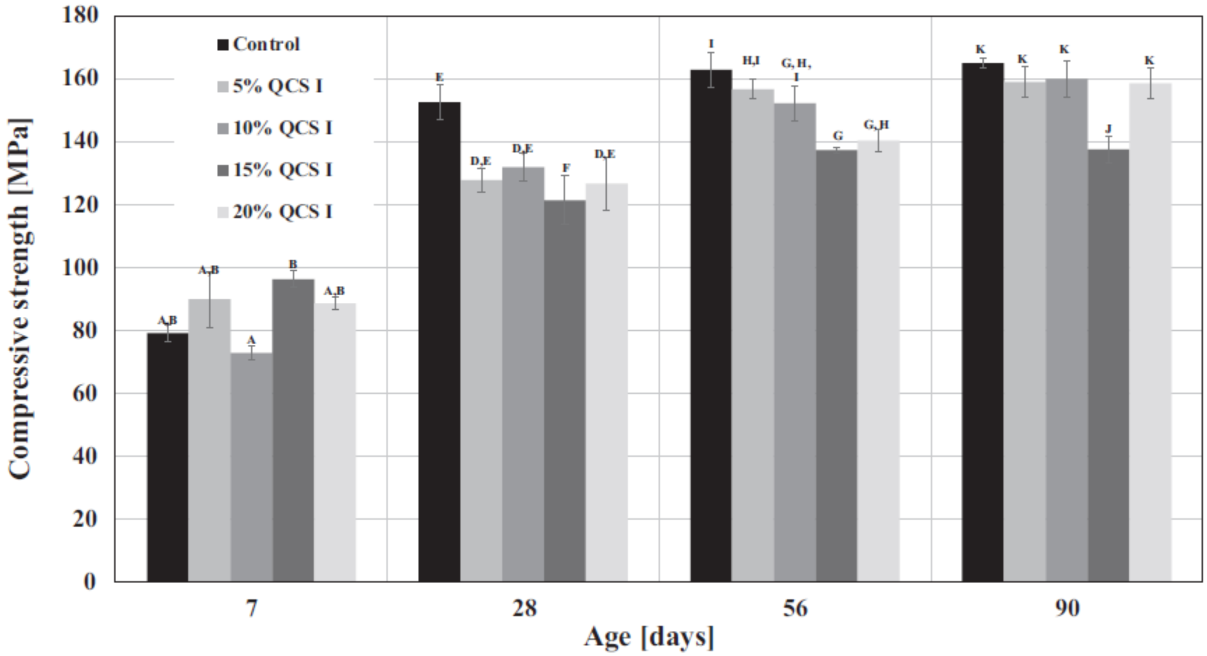

Figure 2.3(a): Mortar compressive strength results of QCS I

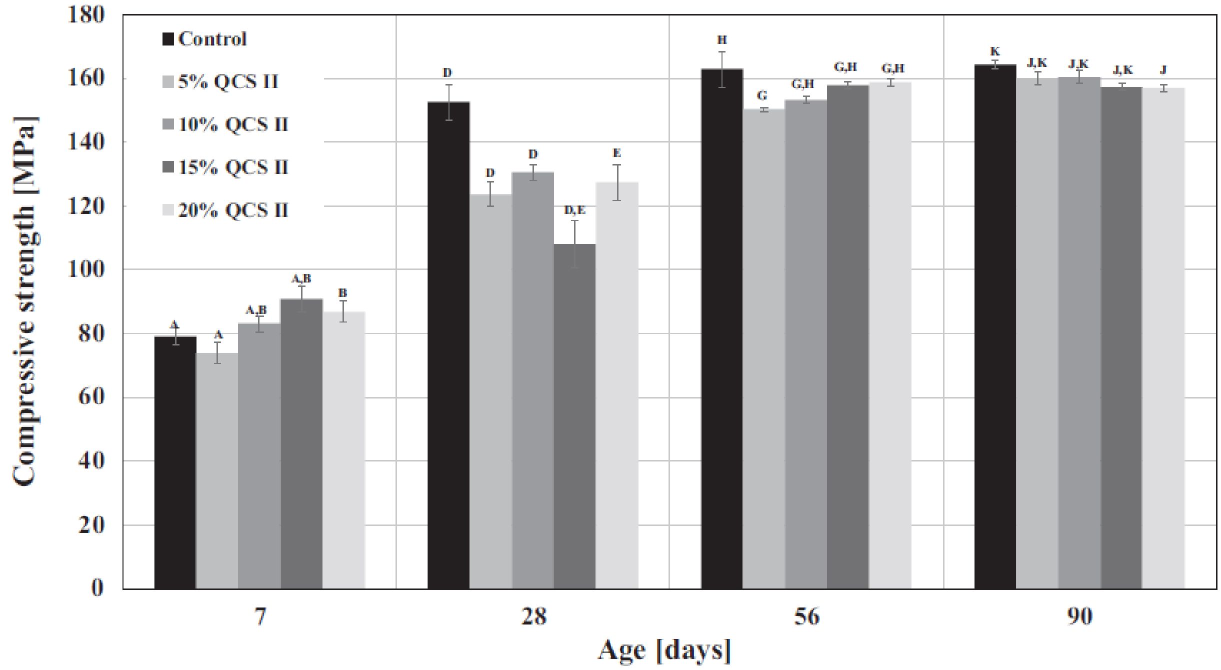

Figure 2.3(b): Mortar compressive strength results of QCS II

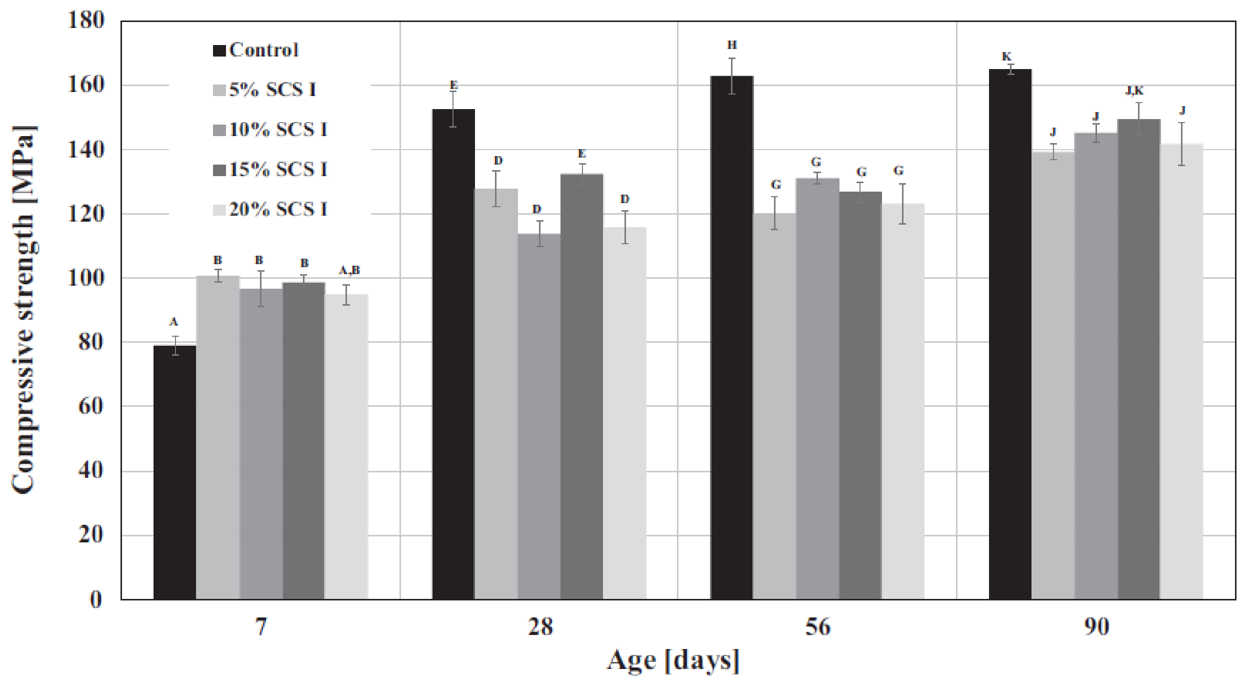

Figure 2.3(c): Mortar compressive strength results of SCS I

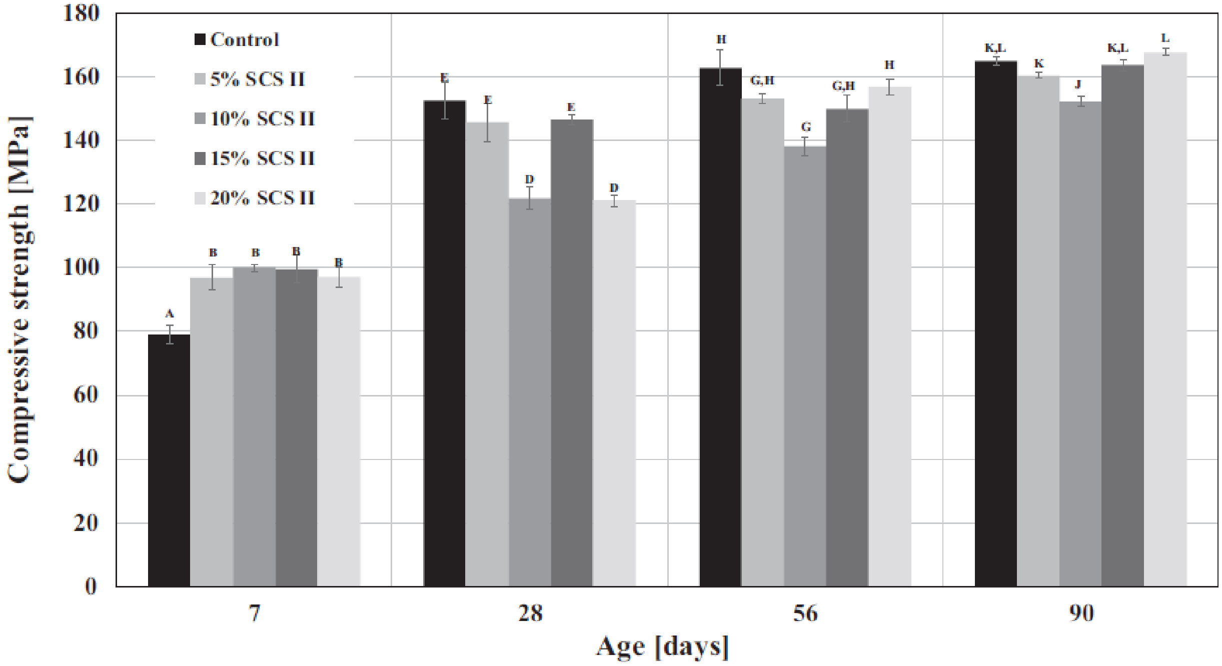

Figure 2.3(d): Mortar compressive strength results of SCS II

Khanzadi and Behnood (2009) [20]

This study was carried out 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 are 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%.

Kumar and Mahesh (2015) [21]

The study was carried out to minimize the cost of cement and sand with concrete mix grade M25 by studying the mechanical behavior of this concrete mix by partial replacing with advanced mineral admixtures such as Copper slag and GGBS in concrete mix. In this study, partial replacement of Cement with GGBS and Sand with Copper Slag was considered. Experimental study is conducted to evaluate the workability and strength characteristics of hardened concrete, properties of concrete have been assessed by partially replacing cement with GGBS, and sand with Copper Slag. The cement has been replaced by GGBS accordingly in the range of 0% (without GGBS), 5%, 10%, 15%, and 20% by weight of cement for M25 mix. The sand has been replaced by Copper slag accordingly in the range of 0% (without Copper slag), 10%, 20%, 30%, and 40% by weight of cement for M25 mix.

It was found that the compressive strength for partial replacement of fine aggregate with copper slag increased in the order of 13.3%, 5.03%, 3.39% & 2.03% for 10%, 20%, 30% & 40% partial replacements respectively and decreased by 11% for 50% partial replacement with respect to control specimen. The split tensile strength for partial replacement of fine aggregate with copper slag increased in the order of 9.06%, 4.43%, 3.35% & 3.32% for 10%, 20%, 30% & 40% partial replacements respectively and decreased by 9.25% for 50% partial replacement with respect to control specimen.

Mirhosseini et al. (2017) [25]

This paper reported the results of an experimental study on the physical and chemical properties of the mineral complex copper slag as a by-product and its effect on the mechanical properties of concrete, for which it constitutes a part of cementitious material. The effects of primary and secondary setting time, and percentage of slag as cementitious material, on the compressive strength of 10x10x10 cm concrete cubic samples, were measured and compared. The mix was optimized for the best use of tailing material share of total cementitious materials, considering the mechanical properties based on the criteria of compressive strength of 7, 14, 28 and 42 days and the optimum percentage of replacement for this cement-like material was specified.

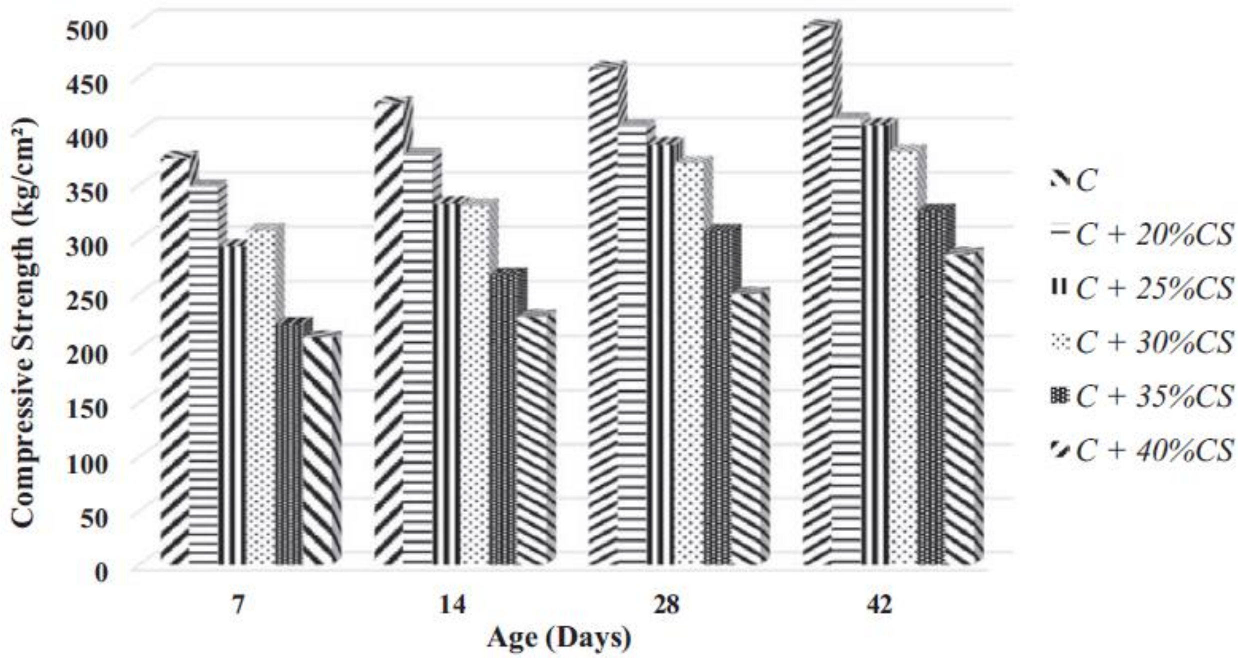

Figure 2.4: Average compressive strength of samples at different ages.

Moura et al. (2007) [26]

This paper presented the results of a study on the use of copper slag as pozzolanic supplementary cementing material for use in concrete. Initially, the chemical and mineralogical characteristics of the copper slag were determined. After this, concrete batches were made with copper slag additions of 20% (relative to the cement weight) and a set of properties were investigated, i.e., specific gravity, compressive strength, splitting-tensile, absorption and absorption rate by capillary suction and carbonation.

The results pointed out that there is a potential for the use of copper slag as a supplementary cementing material to concrete production.

Table 2.1: Density, Compressive strength and split tensile strength of reference mix and mix with replacement of cement with 20% copper slag at w/c ratios of 0.40, 0.50 & 0.60. **(Moura et al., 2007)**

S.No.	Mix	Density (kg/dm3)	CS(Mpa)-C.V.(%)	STS (Mpa)-C.V.(%)
1	REF40	2.52	38.7 (4.31)	3.90 (6.78)
2	REF50	2.48	28.1 (2.96)	3.23 (6.44)
3	REF60	2.46	22.0 (1.82)	2.95 (7.10)
4	COB20%-40	2.58	39.6 (1.54)	4.40 (4.55)
5	COB20%-50	2.54	34.8 (6.08)	3.80 (5.26)
6	COB20%-60	2.49	28.7 (3.51)	3.20 (6.25)

Patnaik et al. (2015) [30]

In this study an experiment was conducted to investigate the strength and durability properties of concrete having copper slag as a partial replacement of sand (fine aggregate). Two different types of Concrete Grade (M20 & M30) were used with different proportions of copper slag replacement (0 to 50%) in the concrete. Strength & Durability properties such as Compressive Strength, Split Tensile Strength, Flexural Strength, Acid Resistivity and Sulphate Resistivity were evaluated for both mixes of concrete. Test results shows that the strength properties of concrete has improved having copper slag as a partial replacement of Sand (upto 40%) in concrete however in terms of durability the concrete found to be low resistant to acid attack and higher resistance against Sulphate attack.

De Schepper et al. (2015) [33]

The motive of this study was to study the use of secondary slags in completely recyclable concrete (CRC). Copper slag was used as a replacement of cement and fine aggregates in mortar. Quickly-cooled copper slag was used for this purpose. Before using the copper slag as a substitution for cement, QCS was milled 3 times during 4 min at 300 rpm in a planetary ball mill (mQCS).

Table 2.2: Average Results of the Compressive Strength Tests (N/mm^2) on Mortar Samples with Copper Slag as Cement (mQCS) or Sand (QCS) Replacement **(De Schepper et al., 2015)**

S.No.	Amount and type of copper slag	7 days	28 days
1	Reference Mortar	31.5 (0.90)	61.5 (0.92)
2	20wt% mQCS	36.8 (0.51)	44.7 (0.49)
3	40wt% mQCS	26.1 (0.17)	34.3 (0.25)
4	60wt% mQCS	13.9 (0.10)	17.2 (0.27)
5	20vol% QCS	54.2 (0.66)	63.4 (0.66)
6	40vol% QCS	50.3 (1.08)	66.9 (0.84)
7	60vol% QCS	53.3 (0.40)	65.3 (0.44)
8	80vol% QCS	52.7 (0.25)	62.7 (0.64)
9	100vol% QCS	48.4 (0.70)	58.2 (0.82)

Singh et al. (2014) [35]

This study investigated the incorporation of copper slag in concrete. The effect of copper slag as partial replacement of cement on the compressive strength of concrete has been investigated. Five concrete mixes (C0, C5, C10, C15 and C20) were made by replacing cement with 5%, 10%, 15% and 20% of copper slag by mass respectively. The water/cement ratio in all the mixes was kept at 0.43. Results showed that the compressive strength of concrete decreases as CS content increases for all curing ages. The reduction in compressive strength is minor up to 10% of CS but beyond 10% of CS, there is significant reduction in compressive strength due to the increase in free water content in mixes.

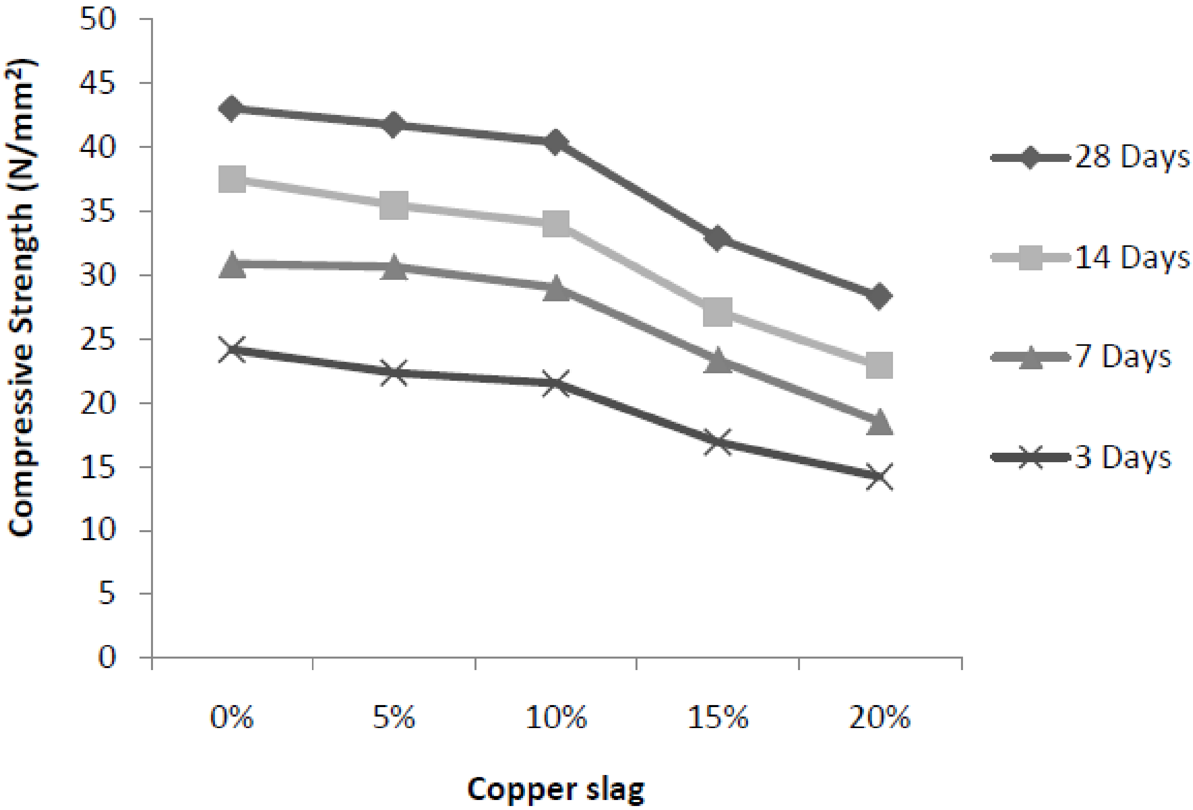

Figure 2.5: Compressive strength of concrete with different replacement levels of copper slag

Sudarvizhi and Ilangovan (2011) [37]

This work reported an experimental procedure to investigate the effect of using copper slag and ferrous slag as partial replacement of sand. The strength characteristics of conventional concrete and slag concrete such as compressive strength, tensile strength were found .Six series of concrete mixtures were prepared with different proportions of CS and FS ranging from 0% to 100%. The test results of concrete were obtained by adding CS and FS to sand in various percentages ranging from 0%, 20%, 40%, 60%, 80% and 100%. All specimens were cured for 7, 28, 60 & 90 days before compression strength test and splitting tensile test. The results indicate that workability increases with increase in CS and FS percentage. The highest compressive strength obtained was 46MPa (for 100% replacement) and the corresponding strength for control mix was 30MPa.

Wu et al. (2010) [38]

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.

2.2 USE OF IRON SLAG AS REPLACEMENT MATERIAL

Humam and Siddique (2013) [13]

In this study effects of replacement of fine aggregate (sand) with high percentages of iron slag on the properties of Mortar. Cement mortars of mix proportion 1:3 with incorporating various percentage of iron slag was designed. Fine aggregate were replace with five percentage of iron slag. The percentages of replacements were 0, 10, 20, 30, and 40% by weight of fine aggregate. Tests were performed for compressive strength, split tensile strength, sulphate resistance, Rapid Chloride Permeability Test.

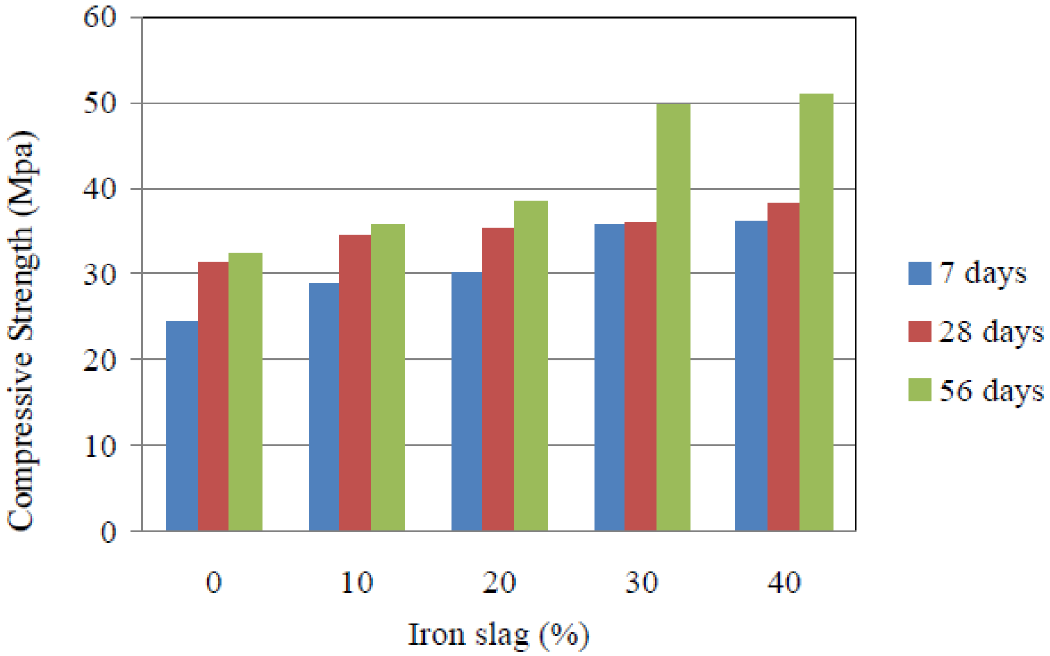

Figure 2.6: Compressive Strength of Mortar

Khajuria and Siddique (2014) [19]

In this paper, the compressive strength of the iron slag concrete was studied. Test specimens of size 150 × 150 × 150 mm were prepared for testing the compressive strength concrete. The concrete mixes with varying percentages (0%, 10%, 20% and 30%) of iron slag as partial replacement of fine aggregate (sand) were cast into cubes for testing.

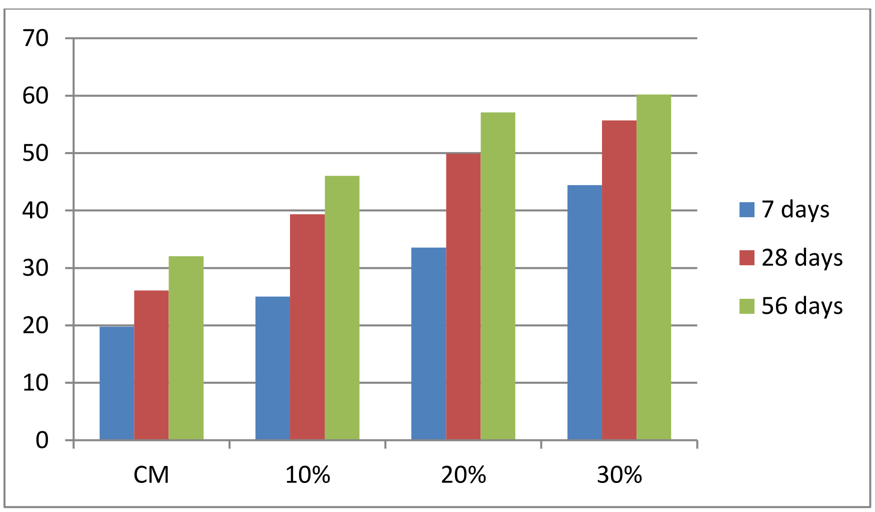

Figure 2.7: Compressive strength of iron slag concrete

Lopez et al. (2015) [24]

An evaluation of durability and mechanical strength in a cement mortar is presented in this work. A slag coming from steelmaking processes has been added to the mortar. This slag has similar properties to the ones of cement, and it has been added to the mortar in different proportions with two sizes of granulometry. With this addition, better properties against the action of sulfates are expected, and therefore, the presence of fracture and wear in the structures can be reduced.

Ouda et al. (2015) [28]

In the present study, the effects of replacing sand by high percentages of basic-oxygen furnace slag on the compressive strength, bulk density and gamma ray radiation shielding properties of mortar have been investigated. Cement mortar of mix proportion 1:3 including various percentages of iron slag was designed. The percentages of replacement were 0%, 40%, 80% and 100% by weight of fine aggregate. Mortar mixes were prepared with water cement ratio of 0.44 and cured in potable water for 90 days. The attenuation measurements were performed using gamma spectrometer of NaI (Tl) detector. The utilized radiation sources comprised 137Cs and 60Co radioactive elements with photon energies of 0.662 MeV for 137Cs and two energy levels of 1.17 and 1.33 MeV for the 60Co. Likewise, half value layer (HVL), tenth value layer (TVL) and the mean free path (mfp) for the tested samples were measured. Results of this investigation indicated that the strength properties of mortars increased significantly upon replacing sand partially by iron slag. It was also observed that the inclusion of iron slag as partial replacement with fine aggregate enhances the bulk density of mortar.

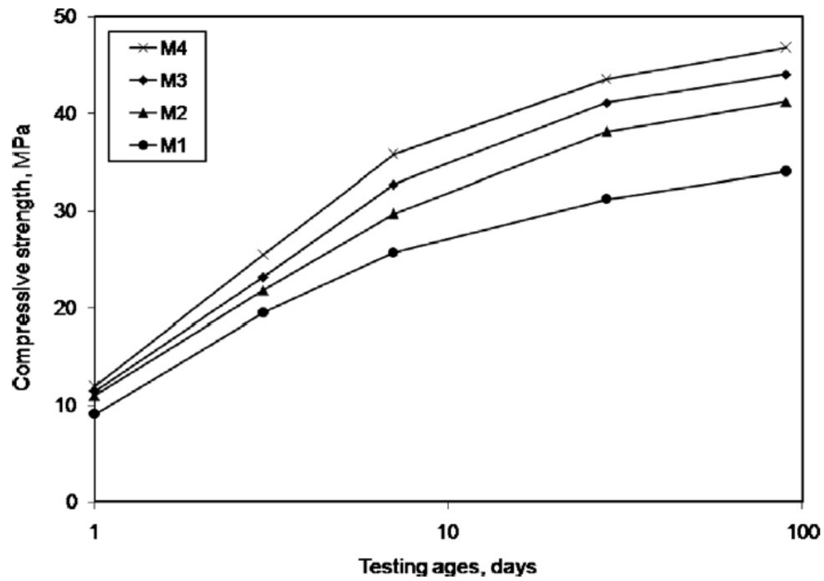

Figure 2.8: Compressive strength of cement mortars due to replacing sand by the basic-oxygen furnace slag at percentages of 0%, 40%, 80% and 100%, submerged in water for 90 days.

Santamaria et al. (2017) [32]

Electric arc-furnace slag (EAFS) is an industrial by-product that can be employed in hydraulic mixes used in the field of construction and civil engineering. The design and preparation of self-compactingmixes with this aggregate is a challenge, due to the loss of workability that always accompanies its use in concrete. Only through careful design of the characteristics and proportions of the components in each mixture will an acceptable workability be achieved. Thus, criteria and methods are proposed in this paper for successful preparation of these types of mixtures. Several concrete mixes are manufactured to obtain self-compaction characteristics and their main properties are analyzed with regard to their use as structural concrete. Electron microscopy observations and dispersive energy analysis are used to study the microstructural features of these mixes. Finally, a numerical simulation is proposed as a useful method that estimates the viscous properties of the mixes and their workability, based on the dosage and the characteristics of their components.

Singh and Siddique (2016) [35]

This paper presents the results on an experimental program carried to explore the possibility of use of iron slag as partial replacement of fine aggregate (sand) in self-compacting concrete (SCC). SCC mixes were designed and fine aggregates were replaced with 0, 10, 25, and 40% iron slag. Tests were performed to evaluate the fresh properties, strength properties and micro-structural analysis of SCC. Properties such as slump flow, V-funnel, U-box, L-box, compressive strength, splitting tensile strength, flexural strength and modulus of elasticity were examined. Results indicated that compressive strength, splitting tensile strength and flexural strength of self-compacting concrete improved with incorporation of iron slag at all the curing ages. SEM and XRD analysis were done to examine the microstructure, which indicated that use of iron slag made the microstructure of SCC denser.

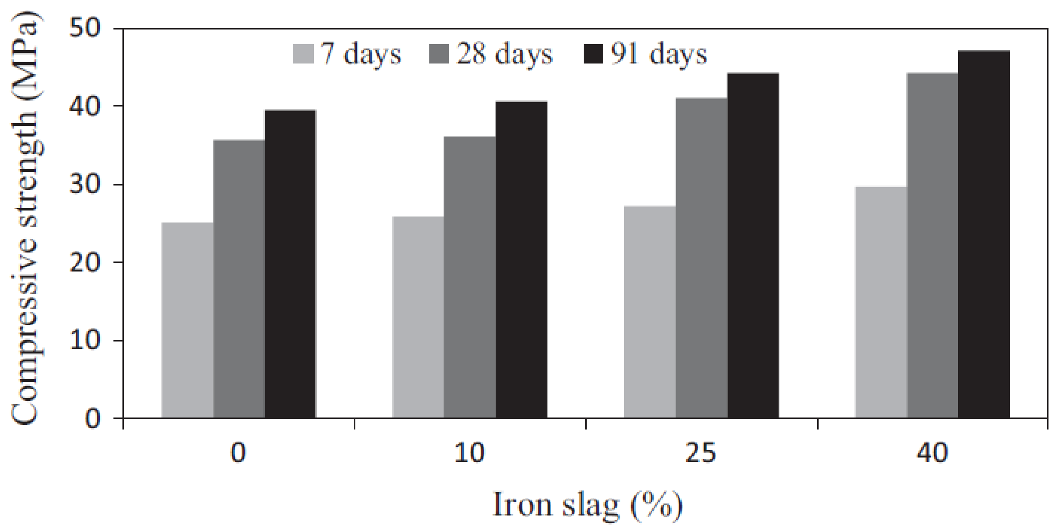

Figure 2.9: Effect of iron slag on compressive strength.

2.3 CONCRETE MIX DESIGN USING TAGUCHI METHOD

Ozbay et al. (2009) [41]

They carried out study of investigation of mix proportions of high strength self compacting concrete by using taguchi method.

The parameters he selected are as follows:

i) water to cementitious material ratio (W/C)

ii) water content (W)

iii) fine aggregate to total aggregate precent (s/a)

iv) fly ash content (FA)

v) air entraining agent content (AE)

vi) super plasticizer content (SP)

The best possible levels for mix proportions are determined for maximization of ultrasonic pulse velocity (UPV), compressive strength, splitting tensile strength and for the minimization of air content, water permeability, and water absorption values.

Three levels for each parameter were selected as follows:

Table 2.3: Parameters and their Levels

W/C (%)	**W (l)**	**s/a (%)**	**FA (%)**	**AE (kg/m^3)**	**SP (kg/m^3)**
30	160	39	15	0.06	8
33	165	43	30	0.07	10
37	170	48	45	0.08	12

Then Standard L_{18} orthogonal array was selected. Then according to the array mix concrete proportions are given as below:

Table 2.4: Details of Mix Concrete Proportions

Trial No.	1	2	3	4	5	6
	W/C (%)	**W (l)**	**s/a (%)**	**FA (%)**	**AE (kg/m^3)**	**SP (kg/m^3)**
1	30	160	39	15	0.06	8
2	30	165	43	30	0.07	10
3	30	170	48	45	0.08	12
4	33	160	39	30	0.07	12
5	33	165	43	45	0.08	8
6	33	170	48	15	0.06	10
7	37	160	43	15	0.08	10
8	37	165	48	30	0.06	12
9	37	170	39	45	0.07	8
10	30	160	48	45	0.07	10
11	30	165	39	15	0.08	12
12	30	170	43	30	0.06	8
13	33	160	43	45	0.06	12
14	33	165	48	15	0.07	8
15	33	170	39	30	0.08	10
16	37	160	48	30	0.08	8
17	37	165	39	45	0.06	10
18	37	170	43	15	0.07	12

Materials: The cement used in this research was a CEM I 42.5 R. It has a specific gravity of 3.12 and Blaine fineness of 3260 cm2/g. Fly ash which is collected from Sugozu thermic central with a Blaine fineness of 2870 cm2/g, and specific gravity of 2.36 is used. A novel polycarboxylic type superplasticizer (SP) is used in all concrete mixtures. Crushed limestone with a maximum nominal size of 16 mm (I) and 19 mm (II) are used as the coarse aggregate. Natural river sand (I) and crushed sand (II) are used as fine aggregate in the concrete mixtures. The coarse and fine aggregates have specific gravities of 2.68 and 2.65 and mean water absorptions of 0.755% and 2.695%, respectively.

Fresh Properties: The concrete temperature, air temperature, air content, slump flow, V funnel flow time and unit weight of fresh concrete are determined. The viscosity of produced concrete is evaluated through the slump flow test. Slump flow range must be 500‑700 mm for SCC. At more than 700 mm the concrete might segregate, and at less than 500 mm the concrete is considered to have significant flow to pass through highly congested reinforcement. The stability of produced concrete is evaluated through the V-shaped funnel test. According to Khayat and Mania a funnel test flow time less than 6 s is recommended for a concrete to qualify for a self compacting. The results of fresh concrete tests are given in Table 4.

Table 2.5: Fresh properties of high strength self compacting concrete

Mix ID	Concrete Temperature °C	Air Temperature °C	Air Content (%)	Slump flow temperature	V funnel flow time	Unit weight km/m^3
M1	22.2	25	3.7	53	6.3	2421
M2	21.1	25.3	3.8	60	5.8	2398
M3	22.8	25.6	4.2	51	5.5	2361
M4	20.7	23.7	3.7	56	5.8	2401
M5	20.3	22	4.3	57	4.6	2379
M6	20.5	20.3	3.4	53	4.8	2393
M7	19.1	23.6	3.6	50	6	2426
M8	22.6	24.5	4.4	55	5.7	2400
M9	23.5	23.5	3.8	55	6.5	2370
M10	19.4	21	3.9	57	6.2	2390
M11	19.3	20	2.7	53	5.8	2431
M12	20.3	22.1	3	64	7.2	2377
M13	18.1	26.2	3.7	67	5.9	2385
M14	18.3	26	4	59	5.6	2421
M15	19.6	24	3.7	65	5.2	2394
M16	19.4	27.2	3.6	57	6	2431
M17	18.9	27.2	3.7	73	5	2437
M18	19.2	27.4	3.1	72	5	2414

As can be seen from Table 2.5 that, slump flow diameter of all mixtures were in the range of 50–73 cm. Although, M17 and M18 exceed the upper limit of slump flow value (70 mm), the authors do not detect any segregation or considerable bleeding in these mixtures. The time measured via the V funnel flow was in the range of 4.6–7.2 s. According to Khayat and Mania V funnel flow time must be less than 6 s. Therefore, M1, M9, M10 and M12 did not fulfill the V funnel flow time criteria. However, these mixtures filled the mold under their own weight without the need for any vibration. Minimum (2.7%) and maximum (4.4%) air content was measured at M11 and M8, respectively.

Hardened Concrete Properties: For each concrete mixes, the compressive strength is determined on three 150 mm cubes at 28 days. Water permeability (TS EN 12390/8) of concrete mixes is determined on three 150 mm cubes samples at 28 days. As rule water permeability testing of specimens begins at least at an age of 28 days. Water pressure may act downwards or upwards on the test specimen.500±50 KPa pressure is applied for 72 h. Drinkable water is used for the test. Immediately after the test, the test specimen is splited in the middle by compression applied on two round steel bars lying on opposite sides, above and below. As soon as the split surface has dried somewhat, the greatest penetration depth in mm and the distribution of the water penetration are established. Splitting tensile strength test are conducted according to the Turkish standard TS 3129 on three 150 mm cubes samples at 28 days. To accept the concrete resistant to the chemical attack, water does not penetrate to a depth of more than 50 mm in concrete likely to come in contact with slightly aggressive media and not more than 30 mm if concrete is likely to come in contact with aggressive media. The test results on hardened concrete can be seen in Table 5.

Table 2.6: Test results of Hardened Concrete

Mix ID	Unit weight km/m3		Water Absorption (%)	UPV (m/s)	Copressive Strength (N/mm2)	Spliting Tensile Strength (N/mm2)	Water Permeability
	Dry	SSD					
M1	2380.7	2411.7	1.3	4335	67.8	4	10
M2	2393	2410.7	0.74	4348	70.8	3.9	9
M3	23723	2393.4	0.89	4323	62.9	4	16
M4	2375	2396.9	0.92	4274	52.4	42	12
M5	2348.6	2370.4	0.93	4190	50.9	3.9	15
M6	2352.5	2374.6	0.94	4121	62.1	4.3	11
M7	2369.9	2402	136	4412	64.5	4.1	19
M8	2368.3	23983	127	4478	63.8	42	17
M9	2368	2400.8	1.38	4412	63.9	43	13
M10	2388.7	2412.1	0.98	4464	74.6	42	12
M11	2413.5	2436.5	0.95	4298	71.6	42	16
M12	2373.9	2395.7	0.92	4274	72.4	4.1	14
M13	2360.8	2385.3	1.04	4323	723	4.8	9
M14	2376	2404.7	121	4373	712	4.7	10
M15	2372.3	2399.9	1.16	4399	70.2	45	7
M16	2387.8	2416	1.18	4438	64.8	4.5	5
M17	23885	2415.1	1.12	4518	64.9	4.8	7
M18	23822	2415.1	1.38	4451	64.1	5	9

In Table 5, each compressive strength, split tensile strength and water permeability values are an average of three 150 mm cube specimens. The compressive strength, split tensile strength and water permeability of high strength self compacting concretes were in the range of 50.9‑74.9, 3.9‑5.0, and 5‑19, respectively. The highest compressive and split tensile strength and the lowest water permeability were measured M10, M18 and M16, respectively. Splitting tensile strengths of all mixtures were in the range 5.5‑8.0% of their compressive strength. The water absorption variation of concrete mixtures was also presented in Table 5. The lowest and highest water absorption was measured in M2 and M18, respectively.

The main effect plots for different properties are given below:

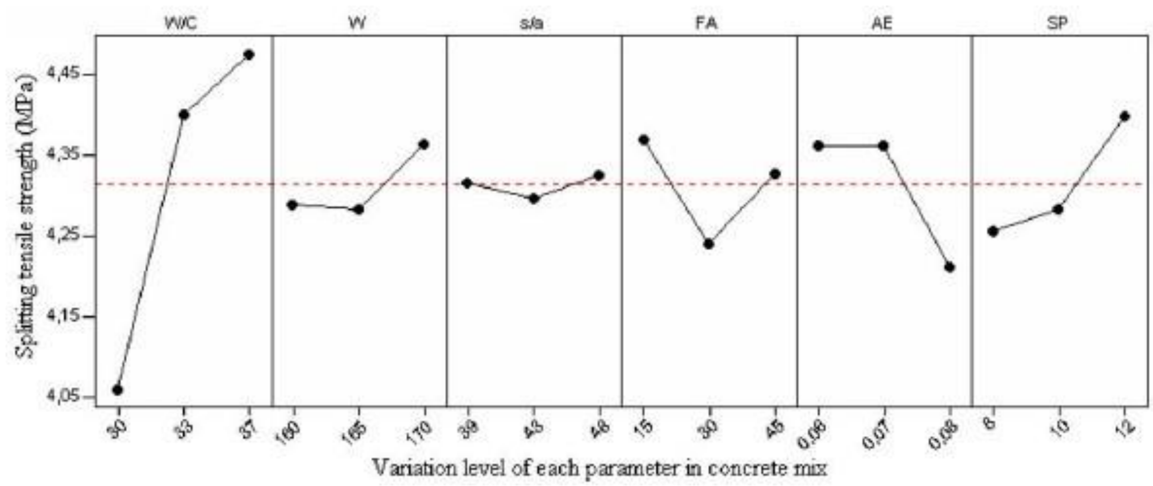

Fig.2.10 (a): Main effect plot for Splitting Tensile Strength Maximization of HSSCC

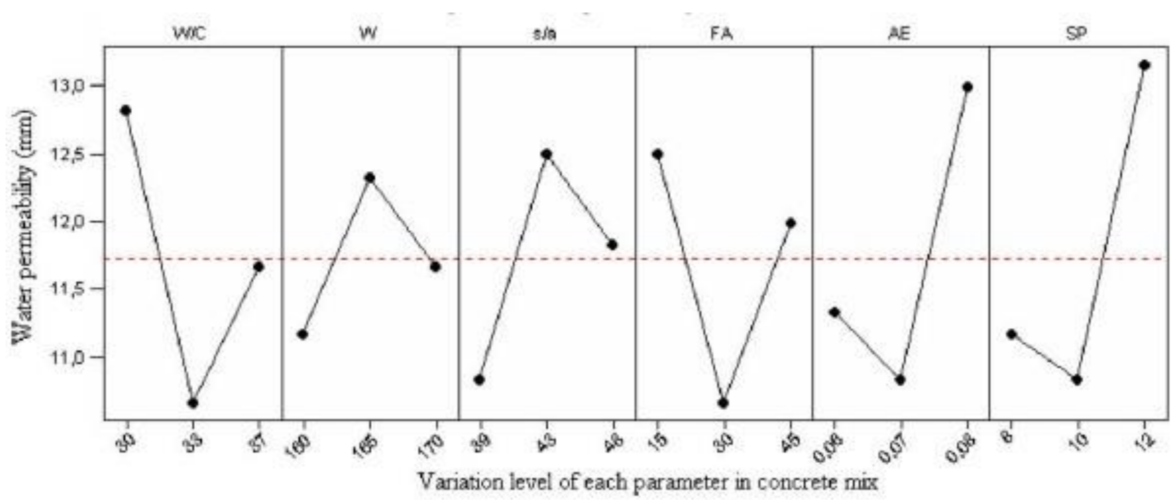

Fig. 2.10 (b): Main effect plot for Water Permeability

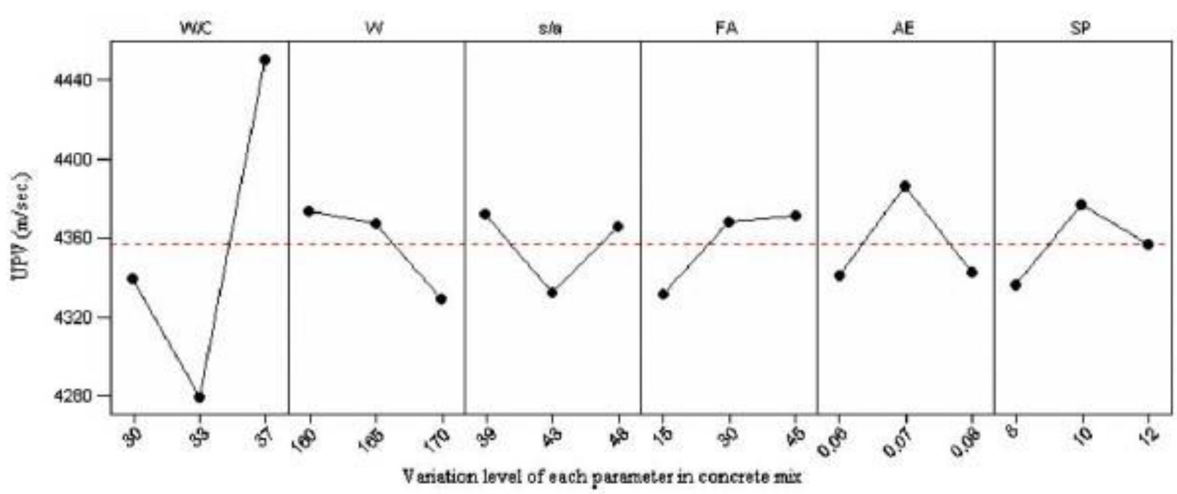

Fig.2.10 (c): Main effect plot for UPV

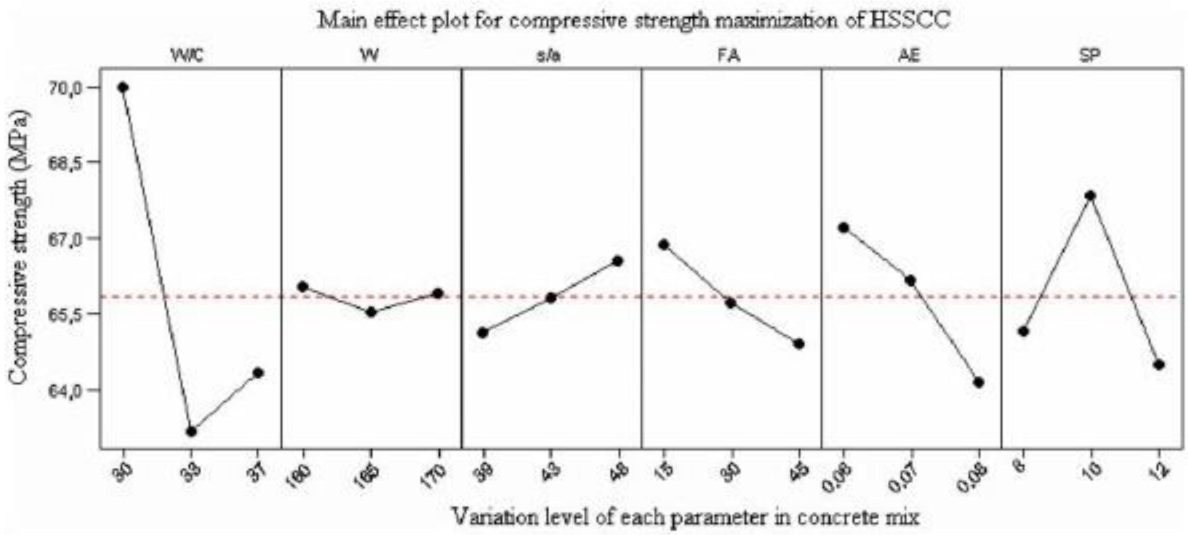

Fig.2.10 (d): Main effect plot for Compressive Strength

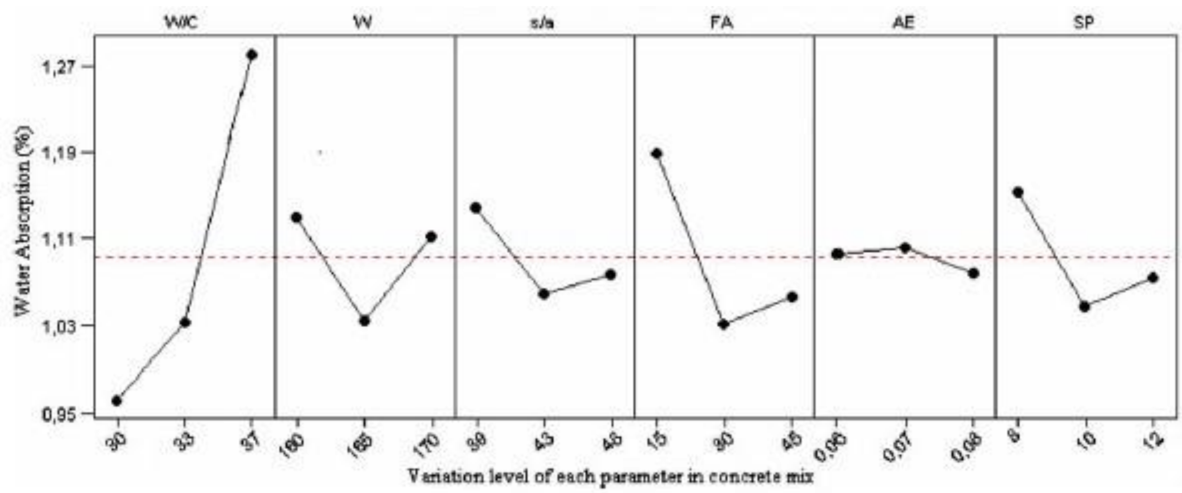

Fig.2.10 (e): Main effect plot for Water Absorption

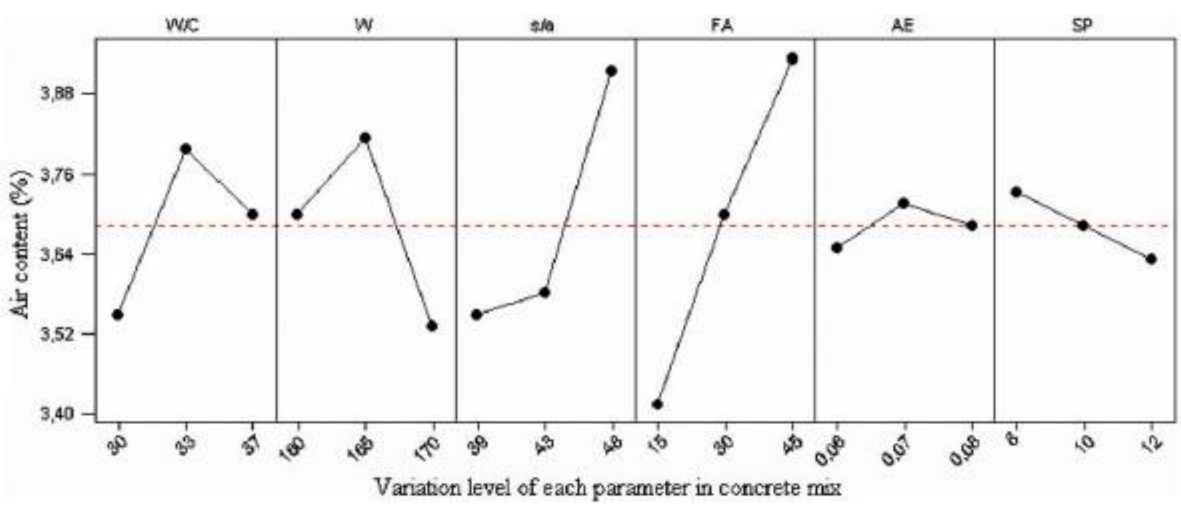

Fig 2.10 (f): Main effect plot for Air Content

The optimal mix design proportions for properties of HSSCC observed from above plots is given in the following table:

Table 2.7: Optimal Mix design proportions

Optimal mix proportions	**W/C (%)**	**W (l)**	**s/a (%)**	**FA (%)**	**AE (kg/m3)**	**SP (kg/m3)**
Ultrasonic pulse Velocity	37	160	39	45	0.07	10
Water permeability	33	160	39	30	0.07	10
Air content	30	170	39	15	0.06	12
Water absorption	30	165	43	30	0.08	10
Splitting tensile Strength	37	170	48	15	0.06	12
Compressive strength	30	160	48	15	0.06	10

Analysis of Variance (ANOVA): The observed values of fresh and hardened concrete properties are the analyzed using ANOVA technique using a commercial software at a 0.05 level of significance to examine the variation in the measured properties of the high strength self compacting concretes. Mix proportions in Table 3 were selected as factors, whereas fresh and hardened properties of the concretes were dependent variables. A statistical analysis was performed to determine the statistically significant factors and data analysis are presented in Table 7. Finally, degree of contribution of the each significant factor was obtained so as to determine the level of its statistical importance in the model. The contribution percentage in Table 7 gives an idea about the degree of contribution of the factors to the measured response. If the contribution percent is high, the contribution of the factors to that particular response is more. Likewise, lower the contribution percent lower the contribution of the factors on the measured response.

Table 2.8: ANOVA Results

Parameter	Statistical parameters	Water absorption	UPV	Water permeability	Splitting tensile strength	Compressive strength	Air content
W/C	DF	2	2	2	2	2	2
	SSS	0.337	90802	14.1	0.6	160.6	2
	ASS	0.337	90802	141	0.6	160.6	2
	MS	0.168	45401	7.1	3	80.3	0.1
	F characteristics	6.07	3.94	0.19	1.61	0.86	33
	Contribution (%)	65.6	74.3	19.2	71.2	65.6	103
W	DF	2	2	2	2	2	2
	SSS	0.031	6878	4.1	0.02	9	2
	ASS	0.031	6878	4.1	0.02	0.9	2
	MS	0.016	3439	2.1	0.01	5	0.1
	F characteristics	0.57	30	0.06	0.07	0.005	0.42
	Contribution (%)	62	5.7	6.1	3.1	0.4	13.6
c/a	DF	2	2	2	2	2	2
	SSS	0.021	5463	8.4	0	62	5
	ASS	0.021	5463	8A	0	6.2	5
	MS	0.01	2731	4.2	0	3.1	0.2
	F characteristics	0.37	24	0.12	0.01	0.03	0.86
	Contribution (%)	4	4.5	12.1	0.4	2.3	275
FA	DF	2	2	2	2	2	2
	SSS	0.086	5875	10.8	0.1	113	0.8
	ASS	0.086	5875	10.8	0.1	113	0.8
	MS	0.043	2937	5.4	0	59	0.4
	F characteristics	155	26	0.15	0.14	0.06	1.4
	Contribution (%)	16.8	4.9	15.2	6.2	4.6	455
AE	DF	2	2	2	2	2	2
	SSS	0.002	7989	15.4	0.1	292	0.01
	ASS	0.002	7989	15.4	0.1	292	0.01
	MS	0.001	3995	7.7	0	14.6	0.01
	F characteristics	0.04	35	21	0.25	0.16	0.02
	Contribution (%)	0.4	6.6	212	11.1	122	0.6
SP	DF	2	2	2	2	2	2
	SSS	0.036	4808	19.1	0.1	375	0.03
	ASS	0.036	4808	19.1	0.1	37.5	0.03
	MS	0.018	2404	9.6	0	18.7	0.02
	F characteristics	0.65	21	26	0.18	0.2	5
	Contribution (%)	7	4	263	8	153	1.6

Hadiwidodo and Mohd, (2010) [39] carried out study on application of Taguchi design of experiments techniques in self compacting concrete (SCC) freshened properties. Six parameters were selected as follows:

A: Coarse aggregate **B:** Fine aggregate **C:** Cement

D: Silica **E:** Water **F:** Super Plasticizer

All of these parameters were given three levels of variation as shown below:

Table 2.9: Parameter and there variation levels

Levels	A: Coarse aggregate (kg/m^3)	B: Fine aggregate (kg/m^3)	C: Cement (kg/m^3)	D: Silica (kg/m^3)	E: Water (kg/m^3)	F: SP (kg/m^3)
1	759	833.98	538.29	43.44	230.14	4.11
2	767.25	826.26	546.2	45.35	233.09	4.48
3	775.5	818.53	554.11	47.26	236.04	4.84

L_{18} Orthogonal array was thus selected with 18 number of trial mixes. The mix proportions so obtained are shown below:

Table 2.10: Details of mix concrete proportions

Experiment Number	Factor 1 A: Coarse (kg m^{-3})	Factor 2 B: Fine (kg m^{-3})	Factor 3 C: Cement (kg m^{-3})	Factor 4 D: Silica Fume (kg m^{-3})	Factor 5 E: Water (kg 112^{-3})	Factor 6 F: p (kg 112^{-3})
1	759	818.53	538.29	43.44	230.14	4.11
2	759	826.26	546.2	45.35	233.09	4.48
3	759	833.98	554.11	47.26	236.04	4.84
4	767.25	818.53	538.29	45.35	233.09	4.84
5	767.25	826.26	546.2	47.26	236.04	4.11
6	767.25	833.98	554.11	43.44	230.14	4.48
7	775.5	818.53	546.2	43.44	236.04	4.48
8	775.5	826.26	554.11	45.35	230.14	4.84
9	775.5	833.98	538.29	47.26	233.09	4.11
10	759	818.53	554.11	47.26	233.09	4.48
11	759	826.26	538.29	43.44	236.04	4.84
12	759	833.98	546.2	45.35	230.14	4.11
13	767.25	818.53	546.2	47.26	230.14	4.84
14	767.25	826.26	554.11	43.44	233.09	4.11
15	767.25	833.98	538.29	45.35	236.04	4.48
16	775.5	818.53	554.11	45.35	236.04	4.11
17	775.5	826.26	538.29	47.26	230.14	4.48
18	775.5	833.98	546.2	43.44	233.09	4.84

Fresh properties: Fresh properties that were analyzed included slump flow, flow time, V-funnel test, L-box and segregation resistance.

The results of fresh concrete properties are given below:

Table 2.11: Results of fresh concrete properties

Experiment Number	Response 1 slump flow (mm)	Response 2 T_{50} (sec)	Response 3 V-funnel (sec)	Response 4 L-box (blocking ratio)	Response 5 segregation resistance (%)
1	740	3.09	9.42	0.98	10.09
2	665	4.95	11.78	0.99	9.49
3	695	4.38	12.91	0.87	6.97
4	740	2.9	12.09	0.84	5.26
5	720	2.76	13.75	0.86	5.48
6	735	3.09	9.09	0.91	6.48
7	720	3.84	12.06	0.9	7.4
8	700	5.48	12.62	0.89	8.7
9	710	5.07	12.75	0.9	1.2
10	705	5.1	12.65	0.91	11.77
11	737.5	3.54	11.73	0.88	9
12	690	5.28	869	0.92	13.52
13	695	4.23	11.41	0.83	7.73
14	680	5.2	11.65	0.8	14.65
15	690	5.73	13.84	0.98	14.16
16	720	3.81	10.52	0.87	13.94
17	710	331	9.54	0.87	13.47
18	717.5	432	937	0.89	13.55

The slump-flow values of all concrete mixtures were in the range of 650- 800 mm, which refers to the mean spread diameter of concrete following the removal of slump cone as specified by EFNARC (2002). The slump-flow Time (T50) of all mixtures were in the range of targeted times (approximately 2-5 s). Additionally, satisfactory blocking resistances were obtained from L-box tests. L-box passing ability ratios of all mixtures were higher than 0.80.

Then the main effect plot graphs are plotted as below:

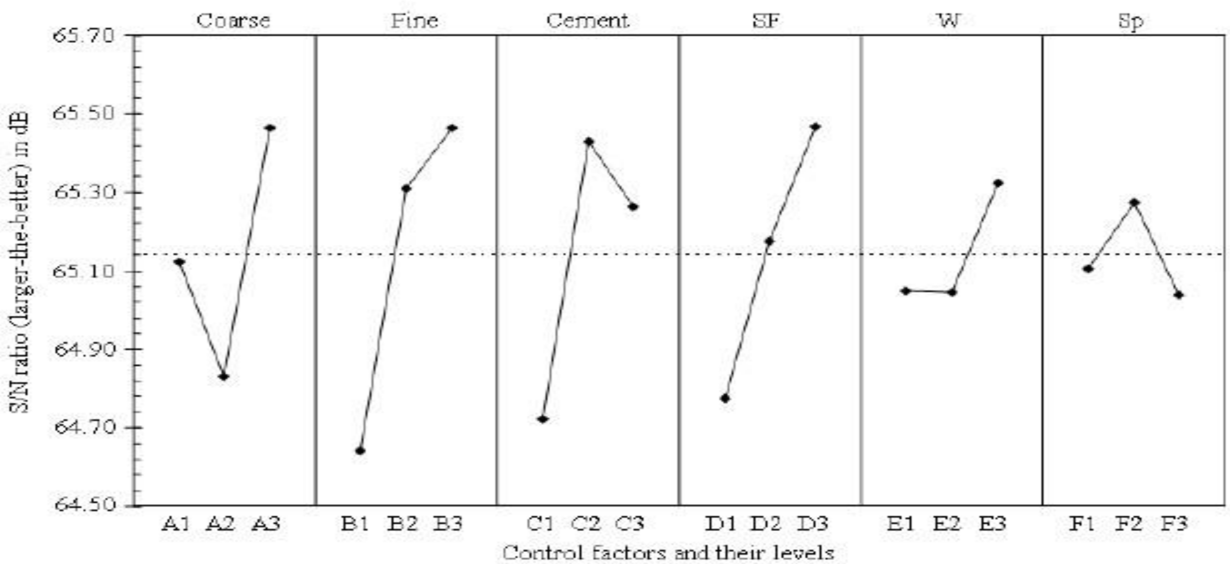

Fig 2.11(a): Factor effect plot for slump flow

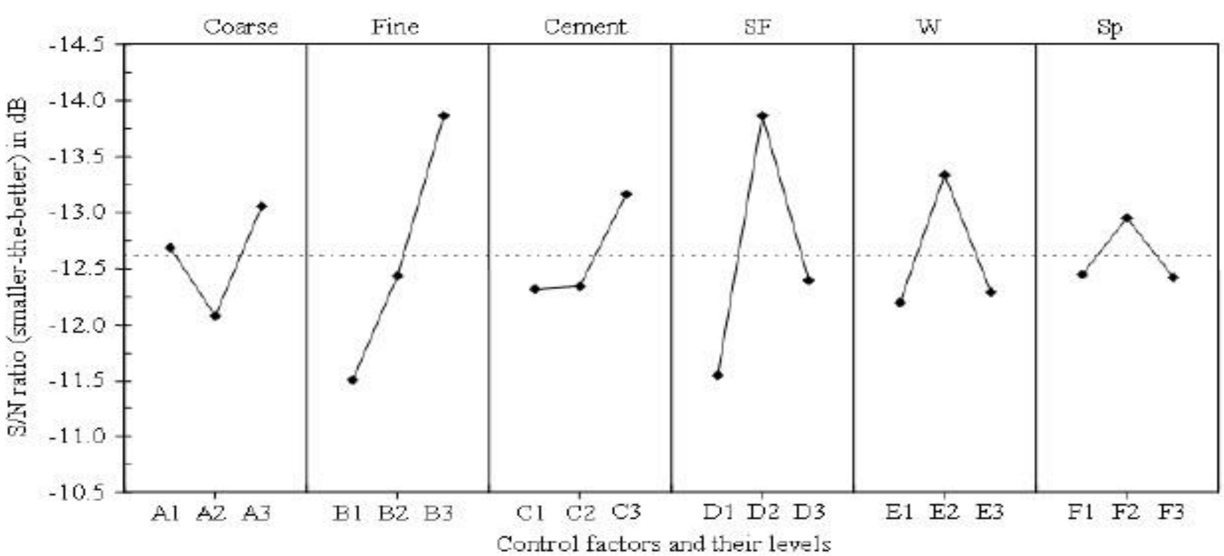

Fig. 2.11(b): Factor effect plot for flow time

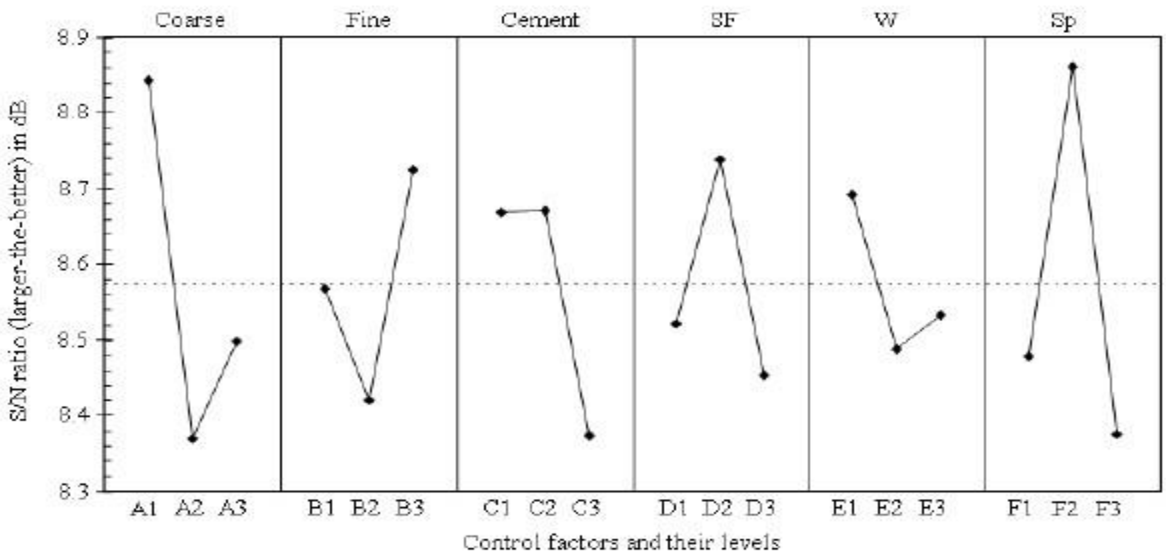

Fig. 2.11(c): Factor effect plot for blocking ratio

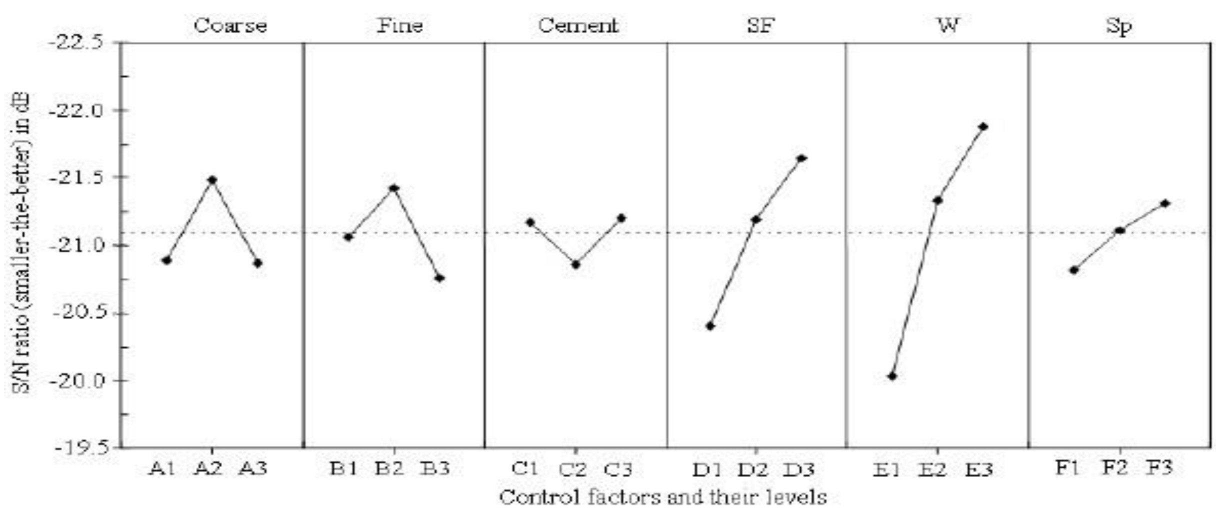

Fig. 2.11(d): Factor effect plot for V-funnel time

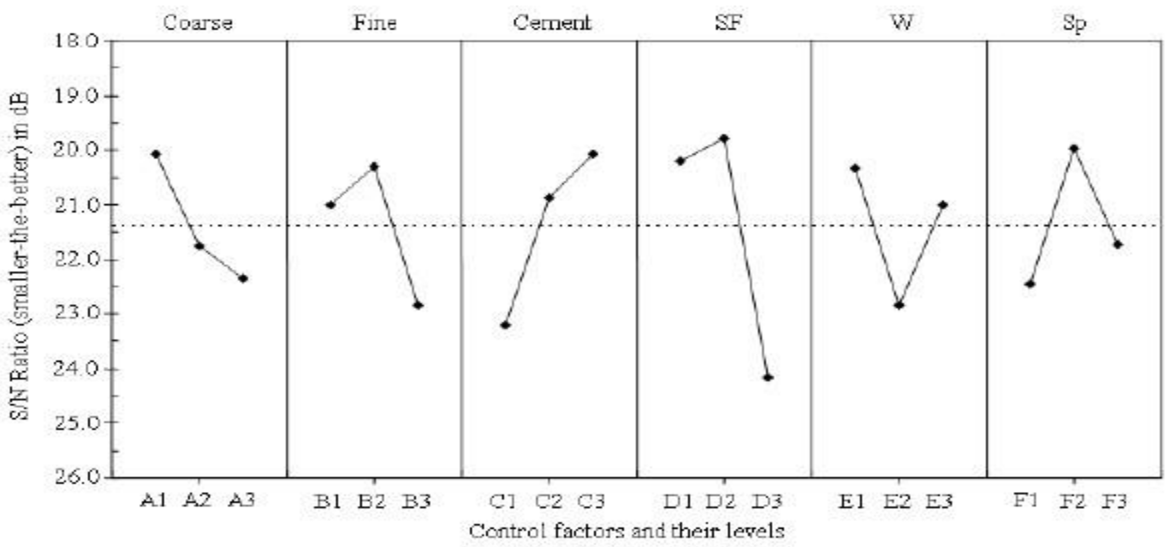

Fig 2.11(e): Factor effect plot for segregation resistance

According to Fig. 1, the optimal mix proportions for slump flow SCC is obtained by A3 B3C2D3E3F2 combinations. The slump flow is increased in the concrete mix within increasing of fine aggregate and silica fume. The optimal mix proportion for flow time SCC is obtained by A3B3C3D2E2F2 combinations. The optimal mix proportion for blocking ratio SCC is obtained by combination of A1B3C2D2E1F2. For the L-box test, the increase of the dosages of water and Sp led to an increase in the L-box blocking ratio. Optimal conditions for Vfunnel time were obtained by mixture combination A2B2C3D3E3F3. When silica fume, water and superplasticizer content are increased in concrete increased the V-flow time.

Olivia and Nikraz (2012) [40] carried out study on properties of fly ash geopolymer concrete designed by Taguchi method. This paper presents an optimization of fly ash geopolymer mixtures by Taguchi method, and a study on the mechanical properties and durability of concrete produced from the optimal mixes. A total of nine mixtures were evaluated.

Following parameters were selected:

i) Aggregate content

ii) Alkaline solution/fly ash ratio

iii) sodium silicate/NaOH ratio

iv) curing method

All of the parameters were given three levels variability as shown:

Table 2.12: Factors and values tested

Factor	Level 1	Level 2	Level 3
A: aggregate content (kg/m^3)	1800	1848	1896
B: alkaline solution/fly ash ratio	0.30	0.35	0.40
C: sodium silicate/NaOH ratio	1.5	2	2.5
D: curing method	24 h to 60 °C	12 h to 70 °C	24 h to 75 °C

Standard L9 orthogonal array was selected. The design mixes are given below:

Table 2.13: Concrete Mix Trials

Trial	Factors			
	Aggregate content (kg/m3)	Alkaline/fly ash ratio	Sodium silicate/NaOH ratio	Curing condition
T1	1800	0.3	1.5	24 h 60 °C
T2	1800	0.35	2	12 h 70°C
T3	1800	0.4	2.5	24 h 75 °C
T4	1848	0.3	2	24 h 75 °C
T5	1848	0.35	2.5	24 h 60 °C
T6	1848	0.4	1.5	12 h 70°C
T7	1896	0.3	2.5	12 h 70°C
T8	1896	0.35	1.5	24 h 75 °C
T9	1896	0.4	2	24 h 60 °C

Optimization of key components of fly ash geopolymer concrete: Compressive strength, weight loss during drying cycles and total weight change after completion of wetting‑drying cycles, sorptivity and AVPV were used as evaluation criteria for the trial mixes. Compressive strength increased with concrete age, except for mixes T3 and T7 (Table 9). The compressive strength of geopolymer is known to vary up to 28 days after curing because continuation of the geopolymerization process after curing; these variations are dependent also on mixture proportions. Mix T7 gave the highest compressive strength at 28 days (54.89 MPa) and mix T9 gave the lowest (29.71 MPa) at

28 days. The high compressive strength of mix T7 may reflect the high aggregate content of this mix.

Table 2.14: Changes of Compressive Strength

Trial mix	Combination	Compressive strength (MPa)		
		1 day	7 days	28 days
T1	A1B1C1D1	37.81	39.52	39.93
T2	A1B2C2D2	34.56	35.31	37.09
T3	A1B3C3D3	49.67	49.89	49.64
T4	A2B1C2D3	41.92	40.93	42.51
T5	A2B2C3D1	32.45	37.55	38.69
T6	A2B3C1D2	25.17	27.16	28.64
T7	A3B1C3D2	54.10	52.29	54.89
T8	A3B2C1D3	32.40	34.53	35.73
T9	A3B3C2D1	25.86	29.29	29.71

Table 10 shows the values of various evaluation criteria after completion of wetting–drying cycles. All mixes showed high compressive strength after 10 wetting-drying cycles in salt water. Changes of compressive strength after the completion of wetting-drying cycles were in the range 19.22–42.85% and weight loss after final drying was in the range 1.97–3.14%, which is low for concrete in an aggressive environment. Our results show that the sorptivity and strength of geopolymer are inversely related. For high strength mixes, sorptivity tends to be low, despite the high AVPV of those mixes. The response index for each factor was calculated by summing the strengths at ages of 1, 7, 28 days for each trial mix that contained that factor dividing by the sum by the number of measurements.

Table 2.15: Compressive strength, weight loss, sorptivity and AVPV of trial mixes.

Trial mix	Combination	Compressive strength after wetting-drying (MPa)	Change in compressive strength (%)	Weight loss during drying process (%)	Total weight change (%)	Sorptivity (mm/ mini's)	AVPV (%)
T1	A1B1C1D1	52.62	33.15	2.65	101.51	0.1324	8.86
T2	A1B2C2D2	50.44	42.85	2.78	101.79	0.1344	9.54
T3	A1B3C3D3	59.48	19.22	2.8	101.14	0.1174	9.87
T4	A2B1C2D3	55.48	35.55	2.55	100.45	0.1034	8.33
T5	A2B2C3D1	47.87	27.48	2.59	101.54	0.128	9.09
T6	A2B3C1D2	38.2	40.65	3.14	101.57	0.1806	9.95
T7	A3B1C3D2	69.81	33.51	1.97	101.04	0.0805	7.42
T8	A3B2C1D3	42.11	21.95	2.76	100.69	0.1538	8.96
T9	A3B3C2D1	37.92	29.46	2.92	101.73	0.1561	10.6

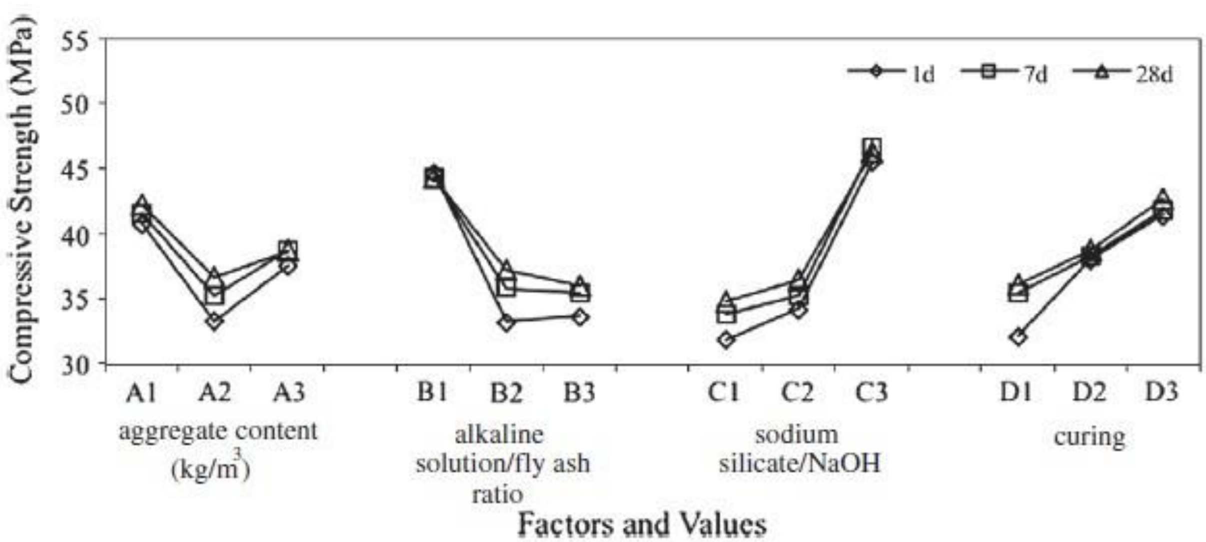

Fig. 2.12: Relationship between compressive strength and the four mix factors and their values.

CHAPTER 3: METHODLOGY & EXPERIMENTAL WORK

3.0 GENERAL

In an experimental study, in order to determine the effects of various factors, which are affecting the results of experiment, different methods and approaches are used. The fundamentals of these methods are the full factorial design and fractional factorial design. In the traditional approach, which is also known as full factorial design, the experiments are performed for each condition, involving all relevant factors. In the experiments where the number of factor and their levels are few, the full factorial experimental design may be applied to the design. 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. Fractional factorial method uses only limited number of combinations and thus is a better method that can be used when the number of parameters is high. Taguchi method is a type of fractional factorial method and was used for the purpose of experimental design. Standard tables known as orthogonal arrays are used for the design of the experiments in the Taguchi method. The analysis uses, the S/N ratio (signal-to-noise), which is a performance characteristic, instead of the average value to interpret the trial result data into a value for the evaluation characteristics in the optimum setting analysis.

In the present study the parameters used included percentage replacement of cement with copper slag and percentage replacement of fine aggregates with iron slag. Effect of change of water-binder ratio was also considered.

3.1 PARAMETERS USED IN THE STUDY

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**,** 2 factors varied at 3-levels were chosen through a pilot study. Taguchi design were used for the design of experiment because it reduces the number of iterations and optimizes the known parameter. The selected parameters were percentage replacement of cement with copper slag and percentage replacement of fine aggregates with iron slag. The levels of replacement each were considered. Cement was partially replaced at 15%, 25% and 35%, whereas, fine aggregates was partially replaced at 10%, 20% and 30% level.

3.2 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, where k is the number of levels for each factor. As, the number of dof for factors is two, and the total dof for the experiment is 2 therefore, L_9 orthogonal array is used in the study carried out. The value of d.o.f for different cases is given as below:

• The degrees of freedom associated with the grand total sum of squares are equal to the number of rows in the design matrix.

• The degree of freedom associated with the sum of squares due to mean is one.

• The degrees of freedom associated with the total sum of squares will be equal to the number of rows in the design matrix minus one.

• The degrees of freedom associated with the factor will be equal to the number of levels minus one.

• The degrees of freedom for the error will be equal to the degrees of freedom for the total sum of squares minus the sum of the degrees of freedom for the various factors.

3.3 ORTHOGONAL ARRAY

Orthogonal arrays provide the best set of well balanced (minimum) experiments. Table 3.1 shows eighteen standard orthogonal arrays along with the number of columns at different levels for these arrays. An array name indicates the number of rows and columns it has, and also the number of levels in each of the columns. For example, array L_4 (2^3) has four rows and three "*2 level*" columns. Similarly the array L_{18} ($2^1 3^7$) has 18 rows; one "*2 level*" column; and seven "*3 level*" columns. Thus, there are eight columns in the array L_{18}. The number of rows of an *orthogonal array* represents the requisite number of experiments. The number of rows must be at least equal to the degrees of the freedom associated with the factors i.e. the control variables. In general, the number of degrees of freedom associated with a factor (control variable) is equal to the number of levels for that factor minus one.

Table 3.1: Standard Orthogonal Arrays

S.No.	**Orthogonal Array**	**No. of Rows**	**Maximum Number of Factors**	**Maximum Number of Columns at these Levels**			
				2	**3**	**4**	**5**
1	L_4	4	3	3	–	–	–
2	L_8	8	7	7	–	–	–
3	L_9	9	4	-	4	–	–
4	L_{12}	12	11	11	–	–	–
5	L_{16}	16	15	15	–	–	–
6	L_{16}	16	5	–	–	5	–
7	L_{18}	18	8	1	7	–	–
8	L_{25}	25	6	–	–	–	6
9	L_{27}	27	13	–	13	–	–
10	L_{32}	32	31	31	–	–	–
11	L_{32}	32	10	1	–	9	–
12	L_{36}	36	23	11	12	-	–
13	L_{36}	36	16	3	13	-	–
14	L_{50}	50	12	1	–	–	11
15	L_{54}	54	26	1	25	–	–
16	L_{54}	54	63	63	–	–	–
17	L_{64}	64	21	–	–	21	–
18	L_{81}	81	40	–	40	–	–

3.4 SIGNAL TO NOISE RATIO

There are three forms of *signal to noise* (S/N) ratio that are of common interest for optimization of static problems.

i) Smaller the Better: This is expressed as:

S/N = $-10Log_{10}(mean\ of\ sum\ of\ squares\ of\ measured\ data)$

This is usually the chosen S/N ratio for all the undesirable characteristics like "*defects*" for which the ideal value is zero. When an ideal value is finite and its maximum or minimum value is defined then the difference between the measured data and the ideal value is expected to be as small as possible.

ii) Larger the Better: This is expressed as:

$$S/N = -10Log_{10}(Mean\ of\ sum\ of\ squares\ of\ reciprocal\ of\ measured\ data)$$

This is often converted to *smaller-the-better* by taking the reciprocal of the measured data and next, taking the S/N ratio as in the *smaller-the-better* case.

iii) Nominal the Best: This is expressed as:

$$S/N = -10Log_{10}(\frac{Square\ of\ mean}{Variance})$$

This case arises when a specified value is the most desired, meaning that neither a smaller nor a larger value is desired.

3.5 STEP WISE PROCEDURE FOR USING TAGUCHI METHOD

The step by step approach for applying the experimental design method in the present study is explained as below

STEP 1: Select the Design Matrix and Perform the Experiments:

Firstly select the suitable parameters. Then select suitable levels of each parameter so as to maximize the response. Then according to the number parameters and number levels for each parameter select the most suitable orthogonal array.

Then the summary statistic (S/N) ratio for an experiment, 'i' is given by:

$$(S/N)_i = -10Log_{10}C_i$$

Where, C_i refers to mean squared effect count for experiment i and the mean square refers to the average of the squares of the 'n' observations in the experiment i, where n is no. of experiments obtained from the orthogonal array.

STEP 2: Calculation of Factor Effects:

The effect of a factor level is defined as the deviation it causes from the overall mean. Hence as a first step, calculate the overall mean value of (S/N) for the experimental region defined by the factor levels.

The effect of a parameter at any level is calculated as the difference of the average S/N ratio for the experiments and overall mean.

STEP 3: Selecting Optimum Factor Levels:

Since –log depicts a monotonic decreasing function; the value of S/N should be maximized. Hence the optimum level for a factor is the level that gives the highest value of S/N in the experimental region.

STEP 4: Developing the Additive Model for Factor Effects:

The relation between S/N and parameters P1, P2, P3, …, Pn can be approximated adequately by the following additive model:

$$S/N\ (Q1, Q2, \dots, Qn) = m + p1 + p2 + \cdots + pn + e -$$

where the term m refers to the overall mean (that is the mean of S/N for the experimental region). The terms p1, p2,…, pn refer to the deviations from μ caused by the setting Q1, Q2, …, Qn of factors P1, P2,…, Pn respectively. The term e stands for the error. In additive model the cross- product terms involving two or more factors are not allowed.

STEP 5: Analysis of Variance (ANOVA):

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. 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

$SS_T = SS_F + SS_E$

Where, $SS_T = \ [\sum_{i=1}^{n} Y_i^2] - \frac{T^2}{N}$

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:

$$MS = \frac{SS}{DF}$$

Where, SS= Sum of squared division

DF= Degree of freedom

STEP 6: Interpretation of ANOVA Table:

In the table the larger the contribution of a particular factor to the total sum of squares, the larger the ability is of that factor to influence S/N. Moreover, the larger the F-value, the larger will be the factor effect in comparison to the error mean square or the error variance.

3.6 MATERIALS USED IN THE EXPERIMENTAL INVESTIGATIONS

3.6.1 Cement: 43 Grade Ordinary Portland Cement (OPC) was used. It was tested in laboratory for its properties as per IS 4031. IS 8112:1989 gives the physical requirements for OPC, 43 Grade. The physical properties of cement are tabulated in table 3.2.

Table 3.2: Physical Properties of Cement

Characteristics	Observed Values	Limits According to IS 8112:1989
Specific Gravity	3.12	---
Fineness (%age retained on 90 micron sieve)	1%	10% (max)
Consistency	27%	---
Initial Setting Time	105 mins.	30 mins. (min)
Final Setting Time	205 mins.	600 mins. (max)
Compressive Strength	3 days: 24.3 N/mm^2 7 days: 36.5 N/mm^2 28 days: 46.6 N/mm^2	23 N/mm^2 (min) 33 N/mm^2 (min) 43 N/mm^2 (min)

3.6.2 Fine Aggregates:

The fine aggregate used for the experimental works is locally procured from Patiala and conformed to grading zone II. Depending upon the particle size distribution IS: 383-1970 has divided the fine aggregate into four grading zones (Grade I to IV). The grading zones become progressively finer from grading zone I to IV. Sieve analysis and physical properties of fine aggregate are tested as per IS: 383-1970, and details are provided in table 3.3 and 3.4.

Table 3.3: Sieve Analysis of Fine Aggregates

S.No.	Size of Sieve	Mass retained (grams)	Percentage Retained (%)	Percentage Passing (%)	Cumulative Percentage Retained (%)
1	4.75mm	10	1	99	1
2	2.36mm	75.5	7.55	91.45	8.55
3	1.18mm	242.5	24.25	67.2	32.8
4	600μ	211	21.1	46.1	53.9
5	300μ	249.5	24.95	21.15	78.85
6	150μ	196	19.6	1.55	98.45
7	Pan	15.5	1.55	0	
	Total	1000			273.55

Table 3.4: Physical Properties of Fine Aggregates

S.No.	Characteristics	Value obtained in testing
1	Specific gravity	2.58
2	Fineness Modulus	2.74
3	Water absorption	1.40%
4	Grading Zone	II
5	Unit Weight (kN/m^3)	16.7 kN/m^3

3.6.3 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 sizes of 20 mm and 10 mm were used in present work. The aggregate were tested as per Indian Standard Specification IS: 383-1970 and the tested characteristics values are provided in table 3.5 to 3.8.

Table 3.5: Sieve analysis of Coarse Aggregates (20mm)

S.No.	Size of Sieve	Mass retained (grams)	Percentage Retained (%)	Percentage Passing (%)	Cumulative Percentage Retained (%)
1	20mm	279	9.30	90.70	9.30
2	10mm	2695	89.83	0.87	99.13
3	4.75mm	20.5	0.68	0.18	99.82
4	Pan	5.5	0.18	0.00	
	Total	3000			208.25
F.M. = (208.25/100)+5 = **7.08**					

Table 3.6: Physical Properties of Coarse Aggregates (20mm)

S.No.	Characteristics	Value obtained in testing
1	Specific gravity	2.58
2	Fineness Modulus	7.08
3	Water absorption	1.00%
4	Oven dry Specific gravity	2.62
5	Unit Weight	14.5 kN/m^3

Table 3.7: Sieve analysis of Coarse Aggregates (10mm)

S.No.	Size of Sieve	Mass retained (grams)	Percentage Retained (%)	Percentage Passing (%)	Cumulative Percentage Retained (%)
1	20mm	0	0.00	100.00	0.00
2	10mm	1266.5	42.22	57.78	42.22
3	4.75mm	1463	48.77	9.02	90.98
4	Pan	270.5	9.02	0.00	
	Total	3000			133.20
F.M. = (133.20/100)+5 = **6.33**					

Table 3.8: Physical Properties of Coarse Aggregates (10mm)

S.No.	Characteristics	Value obtained in testing
1	Specific gravity	2.67
2	Fineness Modulus	6.33
3	Water absorption	0.90%
4	Oven dry Specific gravity	2.7
5	Unit Weight	16.7 kN/m^3

3.7 TEST METHODS

The test methods include designing of concrete mixtures or concrete mix proportioning, casting, curing and testing of cubical specimens. The details of the relevant testing procedures presented in succeeding sections.

3.7.1 Concrete Mix Design

The concrete mixes were designed using guidelines of IS: 10262:2009. Mixes were designed for three different water to binder ratios of 0.4, 0.44 and 0.48. The standard concrete mix design proportions are shown in Table 3.9. Those mixes were proportioned without any use of copper slag and iron slag as per Taguchi Design.

Table 3.9: Standard Concrete Mix Proportions

Trail Mix	W/C	Cement	Fine Aggregates (kg/m^3)	CA(20mm) (kg/m^3)	CA(10mm) (kg/m^3)	Water
CM1	0.4	425	701.66	435.32	675.75	170
CM2	0.44	386.36	728.03	437.55	679.22	170
CM3	0.48	354.17	752.72	438.32	680.42	170

3.7.2 Concrete Mix Design Proportions

As per Taguchi Method, L_9 Orthogonal Array was selected. Out of the four parameters of L_9 orthogonal array only two were selected which were copper slag as partial replacement of cement and iron slag as partial replacement of fine aggregates. The orthogonal array is presented in table 3.10.

Table 3.10: L_9 Orthogonal Array

Mix No.	**Parameters**					
		1	**2**		**3**	**4**
1		1	1		1	1
2		1	2		2	2
3		1	3		3	3
4		2	1		2	3
5		2	2		3	1
6		2	3		1	2
7		3	1		3	2
8		3	2		1	3
9		3	3		2	1

Table 3.11 shows the corresponding variable factors and there levels of replacement as per the L_9 array.

Table 3.11: Variable parameters and their levels of trial mixtures.

Mix No.	**Parameters**	
	Copper Slag as Cement Replacement (%)	**Iron Slag as Fine aggregates replacement (%)**
1	15	10
2	15	20
3	15	30
4	25	10
5	25	20
6	25	30
7	35	10
8	35	20
9	35	30

Table 3.12 shows the concrete mixture proportions for each of the three water-binder ratios as per the L_9 array parameters. Here in the cement and fine aggregates are partially replaced with copper slag and iron slag, respectively.

Table 3.12(a): Composition of test samples for the w/b ratio of 0.4

Trail Mix	W/B	Cement	Copper slag	Iron Slag	Fine Aggregate	CA(20mm)	CA(10mm)	Water
DM1	0.4	361.25	63.75	89.89	632.51	436.01	676.84	170
DM2	0.4	361.25	63.75	179.78	562.23	436.02	676.84	170
DM3	0.4	361.25	63.75	269.68	491.95	436.02	676.84	170
DM4	0.4	318.75	106.25	89.99	633.19	436.48	677.56	170
DM5	0.4	318.75	106.25	179.97	562.83	436.48	677.56	170
DM6	0.4	318.75	106.25	269.96	492.48	436.48	677.56	170
DM7	0.4	276.25	148.75	90.08	633.86	436.95	678.29	170
DM8	0.4	276.25	148.75	180.17	563.43	436.95	678.29	170
DM9	0.4	276.25	148.75	270.25	493	436.95	678.29	170

Table 3.12(b): Composition of test samples for the w/b ratio of 0.44

Trail Mix	W/B	Cement	Copper slag	Iron Slag	Fine Aggregate	CA(20mm)	CA(10mm)	Water
DM10	0.44	328.41	57.95	93.25	656.17	438.18	680.19	170
DM11	0.44	328.41	57.95	186.51	583.26	438.18	680.19	170
DM12	0.44	328.41	57.95	279.76	328.41	438.18	680.19	170
DM13	0.44	289.77	96.59	93.34	656.80	438.60	680.84	170
DM14	0.44	289.77	96.59	186.69	583.82	438.60	680.84	170
DM15	0.44	289.77	96.59	280.03	510.84	438.60	680.84	170
DM16	0.44	251.14	135.23	93.43	657.42	439.01	681.49	170
DM17	0.44	251.14	135.23	186.86	584.38	439.01	681.49	170
DM18	0.44	251.14	135.23	280.30	511.33	439.01	681.49	170

Table 3.12(c): Composition of test samples for the w/b ratio of 0.48

Trail Mix	W/C	Cement	Copper slag	Iron Slag	Sand	CA(20mm)	CA(10mm)	Water
DM19	0.48	301.04	53.13	96.40	678.33	438.89	681.30	170
DM20	0.48	301.04	53.13	192.81	602.96	438.89	681.30	170
DM21	0.48	301.04	53.13	289.21	527.592	438.89	681.30	170
DM22	0.48	265.63	88.54	96.49	678.91	439.27	681.89	170
DM23	0.48	265.63	88.54	192.97	603.48	439.27	681.89	170
DM24	0.48	265.63	88.54	289.46	528.04	439.27	681.89	170
DM25	0.48	230.21	123.96	96.57	679.50	439.65	682.48	170
DM26	0.48	230.21	123.96	193.14	604.00	439.65	682.48	170
DM27	0.48	230.21	123.96	289.71	528.50	439.65	682.48	170

3.7.3 Casting of Specimens

The concrete specimens in the form of cubes of size 150x150x150 mm were casted. Six cubes of each of above design mixes were casted for the mixes proportioned for three w/b ratios of 0.4, 0.44 & 0.48. Three specimens each were subsequently tested for curing periods of 7 & 28 days, respectively. Moulds were firstly cleaned properly and then oiled so that the concrete mix does not stick to the surface of mould. The moulds were then tightened to correct dimension. 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, cement and replacement by-products were added. These were mixed to a uniform color. Then water was added carefully so that no water was lost during mixing. Moulds were then placed on the vibrating table and filled in three layers. The moulds were then picked up from vibrators when the cement slurry appeared on the top. Plate 3.1 shows the process of concrete mixture being prepared. Plate 3.2 shows the cast concrete moulds.

3.7.4 Curing of Specimens

The moulds were demoulded after 24 hours with care. They were then kept in curing tank for a period of 6 and 27 more days, respectively. The temperature of curing tank was maintained at $27^{o} \pm 2^{o}C$. Plate 3.3 shows the specimens being cured in the curing tank.

Plate 3.1: Concrete Mixture Preperation

Plate 3.2: Cast Concrete Moulds

Plate 3.3: Curing of Specimens in Curing Tank

3.7.5 Testing of Specimens

All the concrete specimens were tested for compressive strength and it was carried out as per IS 516:1979. Cubical specimen of size 150 mm were cast for conducting compressive strength test for each mix. The compressive strength test was carried out (each for 3 specimens) at the end of 7 days and 28 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. Plate 3.4 shows the specimens being tested and Plate 3.5 shows a crushed concrete specimen.

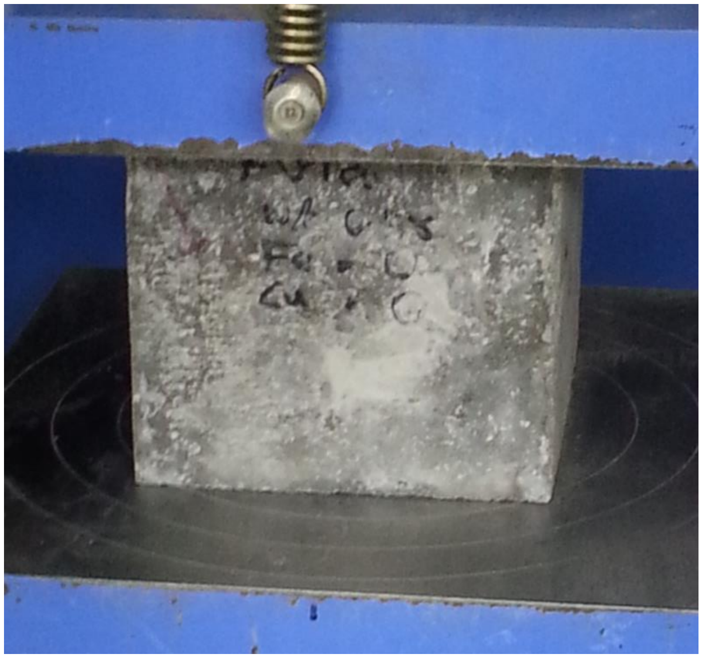

Plate 3.4: Test sample placed in the compression testing machine.

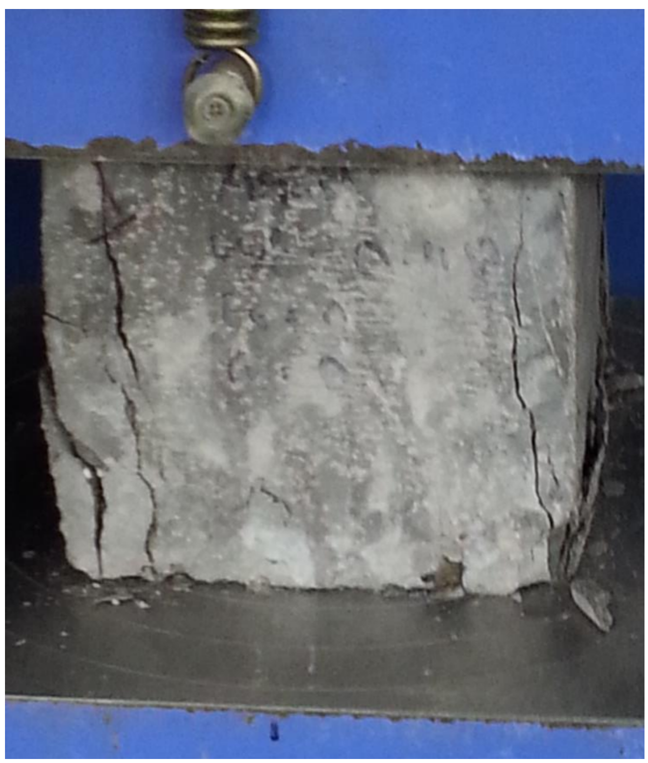

Plate 3.5: Crushed sample during testing.

CHAPTER 4: TAGUCHI ANALYSIS & ANOVA OF RESULTS

4.0 GENERAL

As discussed in previous chapter, cubes of size 150x150x150 mm were casted for compression testing for the laid down experimental program. Six sets of L_9 trial mixes for each combination of 0.4, 0.44 & 0.48 w/b ratio for testing after 7 & 28 days curing time were prepared. Control mixes for each of w/b ratios and curing periods were also cast. The results were then analyzed using Taguchi analytical approach. Analysis of Variance (ANOVA) method was then applied to see the effect of different parameters on the compressive strength.

4.1 COMPRESSIVE STRENGTH RESULTS

The compressive strength results of both control mixes and design mixes are presented in table 4.1(a) to 4.1(d).

Table 4.1(a): Compressive Strength Results for Control Mixes

Mix No.	W/B ratio	Average Compressive Strength (N/mm^2)	
		7 days	28 days
CM1	0.4	42.1	52.9
CM2	0.44	40.9	49
CM3	0.48	37.2	47.2

Table 4.1(a) shows the compressive strength results of control mixes. CM1 with w/b ratio of 0.4 was found to have highest strength.

Table 4.1(b): Compressive Strength Results for Design Mixes with w/b ratio of 0.4

Trial No.	Copper Slag (%)	Iron Slag (%)	Average Compressive Strength (N/mm^2)		S/N Ratio (dB)	
			7 days	28 days	7 days	28 days
DM1	15	10	38.47	45.20	26.88	28.28
DM2	15	20	38.43	47	26.91	28.64
DM3	15	30	41.2	48.13	27.52	28.87
DM4	25	10	32.96	36.33	25.54	26.43
DM5	25	20	36.26	37.4	26.41	26.64
DM6	25	30	35.83	42.03	26.26	27.63
DM7	35	10	29.9	36.96	24.59	26.56
DM8	35	20	30.66	39.16	24.94	27.08
DM9	35	30	32.8	38.53	25.52	26.94

From table 4.1(b) it is observed that for the mixes with w/b ratio of 0.4, control mixes have more compressive strength than design mixes having partial replacement materials. Among design mixes, as per trend observed for w/b ratio of 0.4, mix DM3 with 15% copper slag replacement and 30% iron slag replacement has shown the highest compressive strength (41.2 N/mm^2 for 7 days curing period & 48.13 N/mm^2 for 28 days curing period) and highest S/N ratio (27.52 dB for 7 days curing period and 28.87 dB for 28 days curing period).

Table 4.1(c): Compressive Strength Results for Design Mixes with w/b ratio of 0.44

Trial No.	Copper Slag (%)	Iron Slag (%)	Average Compressive Strength (N/mm^2)		S/N Ratio (dB)	
			7 days	28 days	7 days	28 days
DM10	15	10	34.2	44.33	25.84	28.03
DM11	15	20	38.4	45.43	26.79	28.37
DM12	15	30	35.73	45.66	26.28	28.4
DM13	25	10	30.36	42.43	24.86	27.72
DM14	25	20	24.93	41.06	22.92	27.49
DM15	25	30	32.53	41.93	25.47	27.65
DM16	35	10	25.96	29.06	23.49	24.4
DM17	35	20	30.4	36.66	24.86	26.5
DM18	35	30	28.63	36.03	24.35	26.32

From table 4.1(c) it is found that for the mixes with w/b ratio of 0.44, again the control mixes have more compressive strength than design mixes having partial replacement materials. Among design mixes, as per trend observed for w/b ratio of 0.44, mix DM12 with 15% copper slag replacement and 30% iron slag replacement has shown the highest compressive strength (35.73 N/mm^2 for 7 days curing period and 45.66 N/mm^2 for 28 days curing period) and highest S/N ratio (26.28 dB N/mm^2 for 7 days curing period and 28.4 dB for 28 days curing period).

Table 4.1(d): Compressive Strength Results for Design Mixes with w/b ratio of 0.48

Trial No.	Copper Slag (%)	Iron Slag (%)	Average Compressive Strength (N/mm^2)		S/N Ratio	
			7 days	28 days	7 days	28 days
DM19	15	10	32.33	41.63	25.39	27.54
DM20	15	20	33.46	42.13	25.64	27.71
DM21	15	30	29.6	39.73	24.64	27.2
DM22	25	10	26.66	32.83	23.69	25.51
DM23	25	20	24.16	32.66	22.88	25.45
DM24	25	30	26.3	34.9	23.59	25.94
DM25	35	10	21.4	29.06	21.82	24.47
DM26	35	20	26.73	31.86	23.76	25.27
DM27	35	30	29.33	37.1	24.54	26.55

From table 4.1(d) it is found that for the mixes with w/b ratio of 0.48, again the control mixes have more compressive strength than design mixes having partial replacement materials. Among design mixes, as per trend observed for w/b ratio of 0.48, mix DM20 with 15% copper slag replacement and 20% iron slag replacement has shown the highest compressive strength (33.46 N/mm^2 for 7 days curing period and 42.13 N/mm^2 for 28 days curing period) and highest S/N ratio (25.64 dB N/mm^2 for 7 days curing period and 27.71 dB for 28 days curing period).

4.2 S/N RATIO RESPONSE TABLES AND MAIN EFFECT PLOTS

Tables 4.2(a)–4.2(f) show the S/N ratio response tables for different w/b ratios of 0.4, 0.44 & 0.48 and curing periods of 7 & 28 days. S/N ratio used here is larger the better. The S/N response tables show that with the increasing level of parameter cement replacement with copper slag the value of S/N ratio is decreasing for all the cases of different w/b ratios and curing times. The highest S/N ratio for this parameter is found to be 28.60 dB for level 1 (15% copper slag replacement), w/b ratio of 0.4 and curing time of 28 days. The delta which is difference between highest and lowest S/N ratios was found to have highest value of 2.52 dB for w/b ratio of 0.44 and 28 days. It is seen that in all the cases of w/b ratios and curing times, the S/N ratio values of parameter Fine aggregates replacement with Iron Slag is found to be increasing. The highest S/N ratio value is found to be 27.82 dB for level 3, w/b ratio of 0.4 and curing time of 28 days. Delta was highest in case of w/b ratio of 0.4 and curing time of 7 days with a value of 0.77 dB. Main effect plots for the S/N ratio response tables are shown in figure 4.1(a)-(b).

Table 4.2(a): S/N Response Table Results for W/B Ratio of 0.4 & Curing Time of 7 days

Response Table for S/N W/B 0.4, Curing Time 7days		
Level	**Cement Replacement with Copper Slag (dB)**	**Fine Agg. Replacement with Iron Slag (dB)**
1	27.11	25.67
2	26.08	26.09
3	25.02	26.44
Delta	2.09	0.77

Table 4.2(b): S/N Response Table Results for W/B Ratio of 0.44 & Curing Time of 7 days

Response Table for S/N W/B 0.44, Curing Time 7days		
Level	**Cement Replacement with Copper Slag (dB)**	**Fine Agg. Replacement with Iron Slag (dB)**
1	26.31	24.73
2	24.42	24.86
3	24.24	25.37
Delta	2.07	0.64

Table 4.2(c): S/N Response Table Results for W/B Ratio of 0.48 & Curing Time of 7 days

Response Table for S/N W/B 0.48, Curing Time 7days		
Level	**Cement Replacement with Copper Slag (dB)**	**Fine Agg. Replacement with Iron Slag (dB)**
1	25.23	23.64

2	23.39	24.10
3	23.38	24.26
Delta	1.85	0.62

Table 4.2(d): S/N Response Table Results for W/B Ratio of 0.4 & Curing Time of 28 days

Response Table for S/N W/B 0.4, Curing Time 28days		
Level	**Cement Replacement with Copper Slag (dB)**	**Fine Agg. Replacement with Iron Slag (dB)**
1	28.60	27.09
2	26.91	27.46
3	26.86	27.82
Delta	1.74	0.73

Table 4.2(e): S/N Response Table Results for W/B Ratio of 0.44 & Curing Time of 28 days

Response Table for S/N W/B 0.44, Curing Time 28days		
Level	**Cement Replacement with Copper Slag (dB)**	**Fine Agg. Replacement with Iron Slag (dB)**
1	28.27	26.72
2	27.63	27.46
3	25.75	27.46
Delta	2.52	0.74

Table 4.2(f): S/N Response Table Results for W/B Ratio of 0.48 & Curing Time of 28 days

Response Table for S/N W/B 0.48, Curing Time 28days		
Level	**Cement Replacement with Copper Slag (dB)**	**Fine Agg. Replacement with Iron Slag (dB)**
1	27.49	25.84
2	25.64	26.15
3	25.44	26.57
Delta	2.05	0.73

MAIN EFFECT PLOTS FOR S/N

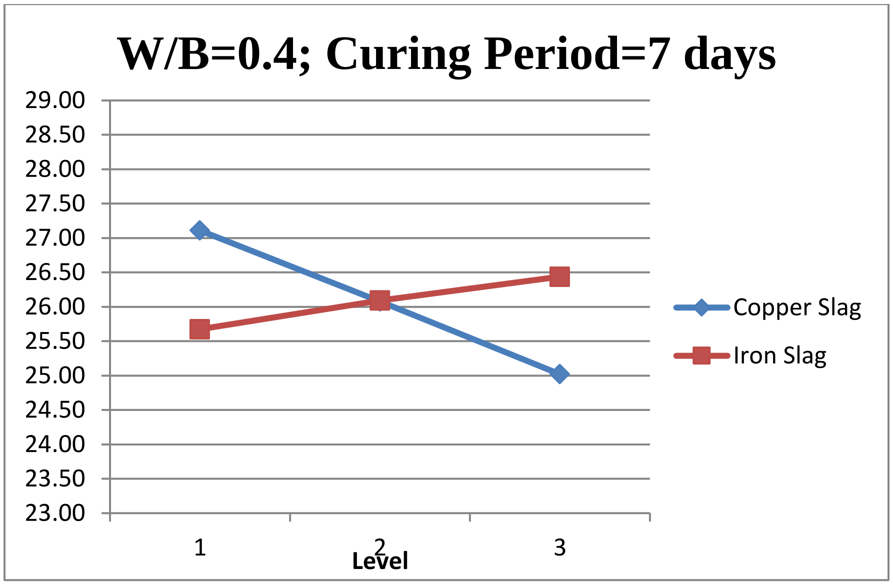

Figure 4.1(a): Main Effect Plot for S/N for w/b=0.4, Curing Period=7 days

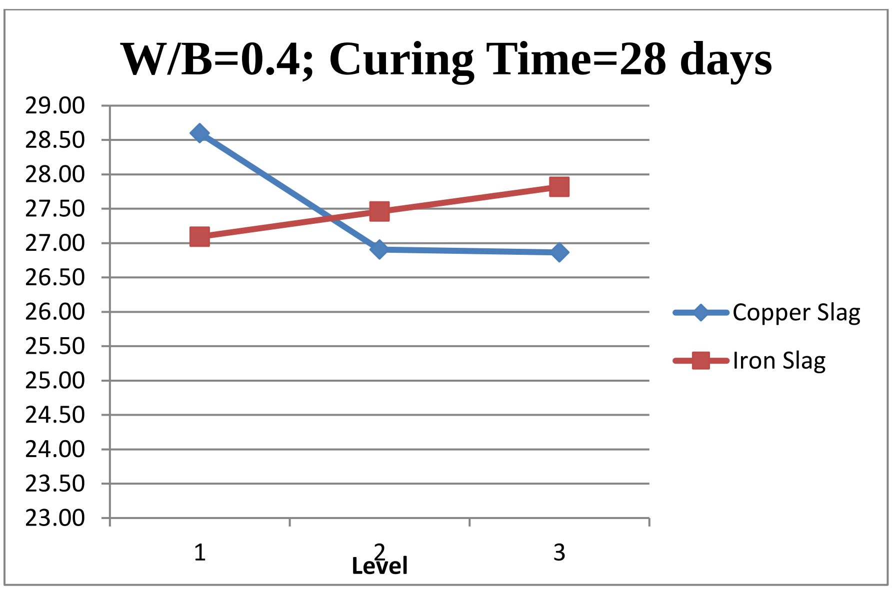

Figure 4.1(b): Main Effect Plot for S/N for w/b=0.4, Curing Period=28 days

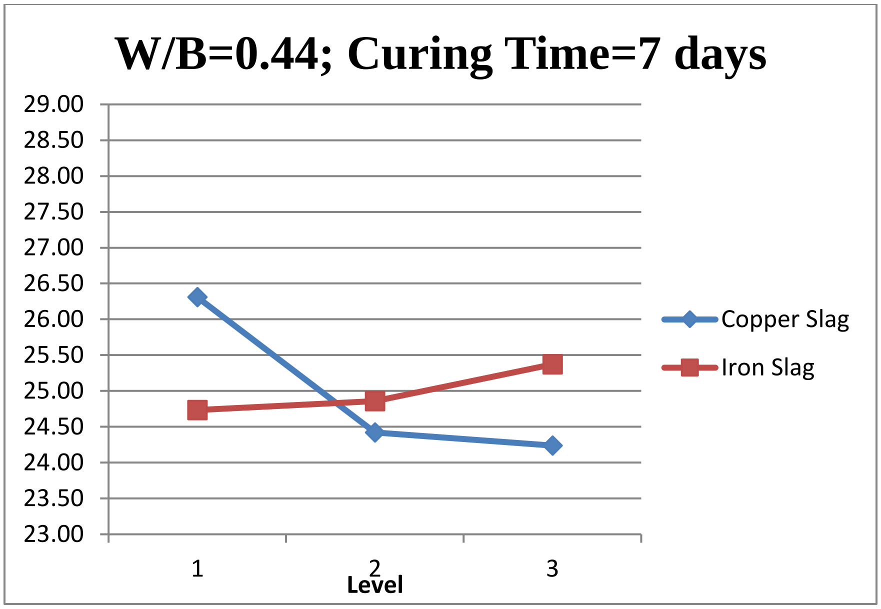

Figure 4.1(c): Main Effect Plot for S/N for w/b=0.44, Curing Period=7 days

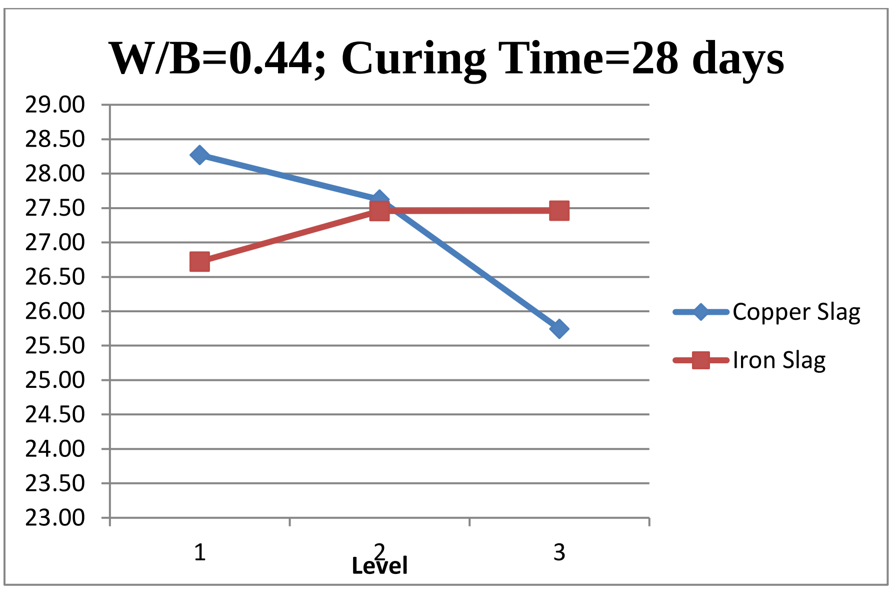

Figure 4.1(d): Main Effect Plot for S/N for w/b=0.44, Curing Period=28 days

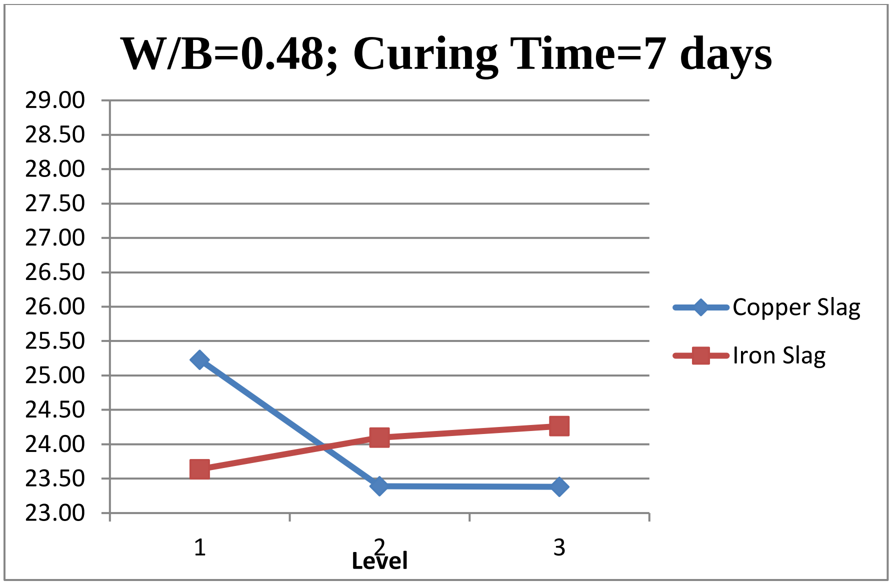

Figure 4.1(e): Main Effect Plot for S/N for w/b=0.48, Curing Period=7 days

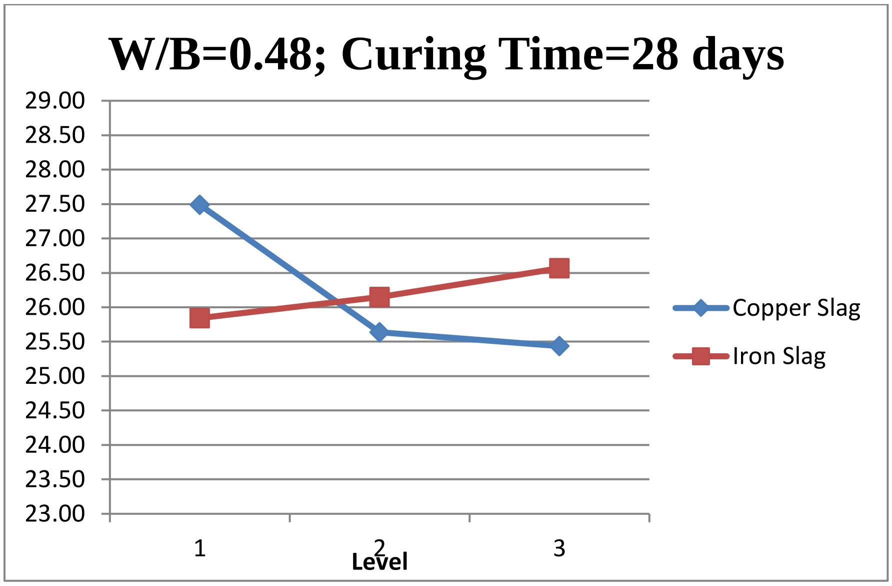

Figure 4.1(f): Main Effect Plot for S/N for w/b=0.48, Curing Period=28 days

4.3 MEAN COMPRESSIVE STRENGTH RESPONSE TABLES AND MAIN EFFECT PLOTS

Tables 4.3(a)–4.3(f) show the mean compressive strength response tables for different w/b ratios of 0.4, 0.44 & 0.48 and curing times of 7 & 28 days. The mean response tables show that with the increasing level of parameter cement replacement with copper slag the value of mean strength is decreasing for all the cases of different w/b ratios and curing times similar to the case of S/N ratio response tables. The highest mean compressive strength for this parameter is found to be 46.78 N/mm^2 for level 1 (15% copper slag replacement), w/b ratio of 0.4 and curing time of 28 days. The highest value of delta is found to be 11.22 N/mm^2 for w/b ratio of 0.44 and 28 days. It is seen that in all the cases of w/b ratios and curing times, the mean compressive strength values of parameter Fine Aggregates replacement with Iron Slag is found to be increasing. The highest mean strength value is found to be 42.90 N/mm^2 for level 3 (30% replacement), w/b ratio of 0.4 and curing time of 28 days. Delta was highest in case of w/b ratio of 0.4 and curing time of 28 days with a value of 3.4 N/mm^2. Main effect plots for the S/N ratio response tables are shown in figure 4.2 (a)-(f).

Table 4.3(a): Mean Response Table Results for W/B Ratio of 0.4 & Curing Time of 7 days

Response Table for Mean W/B 0.4, Curing Time 7days		
Level	**Cement Replacement with Copper Slag (MPa)**	**Fine Agg. Replacement with Iron Slag (MPa)**
1	39.37	33.78
2	35.02	35.12
3	31.12	36.61
Delta	8.25	2.83

Table 4.3(b): Mean Response Table Results for W/B Ratio of 0.44 & Curing Time of 7 days

Response Table for Mean W/B 0.44, Curing Time 7days		
Level	**Cement Replacement with Copper Slag (MPa)**	**Fine Agg. Replacement with Iron Slag (MPa)**
1	36.11	30.18
2	29.28	31.24
3	28.33	32.30
Delta	7.78	2.12

Table 4.3(c): Mean Response Table Results for W/B Ratio of 0.48 & Curing Time of 7 days

Response Table for Mean W/B 0.48, Curing Time 7days		
Level	**Cement Replacement with Copper Slag (MPa)**	**Fine Agg. Replacement with Iron Slag (MPa)**
1	31.80	26.80
2	25.71	28.12
3	25.82	28.41
Delta	5.98	1.61

Table 4.3(d): Mean Response Table Results for W/B Ratio of 0.4 & Curing Time of 28 days

Response Table for Mean W/B 0.4, Curing Time 28days		
Level	**Cement Replacement with Copper Slag (MPa)**	**Fine Agg. Replacement with Iron Slag (MPa)**
1	46.78	39.50
2	38.59	41.19
3	38.22	42.90
Delta	8.56	3.4

Table 4.3(e): Mean Response Table Results for W/B Ratio of 0.44 & Curing Time of 28 days

Response Table for Mean W/B 0.44, Curing Time 28days		
Level	**Cement Replacement with Copper Slag (MPa)**	**Fine Agg. Replacement with Iron Slag (MPa)**
1	45.14	38.61
2	41.81	41.06
3	33.92	41.21
Delta	11.22	2.6

Table 4.3(f): Mean Response Table Results for W/B Ratio of 0.48 & Curing Time of 28 days

Response Table for Mean W/B 0.48, Curing Time 28days		
Level	**Cement Replacement with Copper Slag (MPa)**	**Fine Agg. Replacement with Iron Slag (MPa)**
1	41.17	34.51
2	33.47	35.56
3	32.68	37.24
Delta	8.49	2.73

MAIN EFFECT PLOTS FOR MEAN COMPRESSIVE STRENGTH

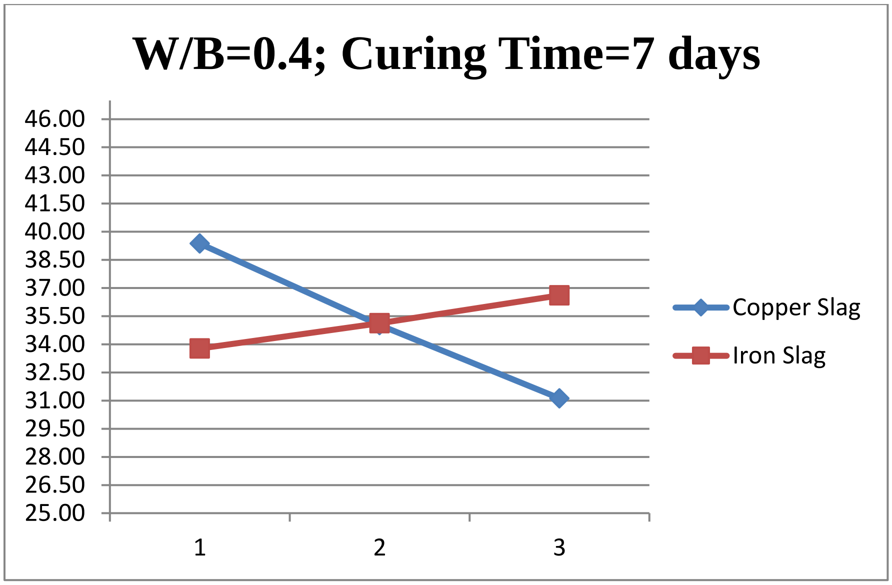

Figure 4.2(a): Main Effect Plot for mean compressive strength for w/b=0.4, Curing Period=7 days

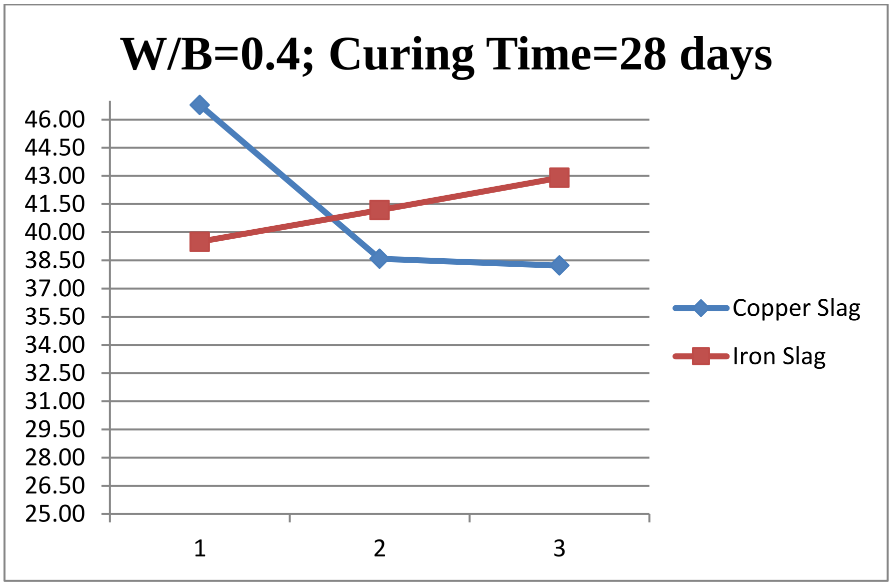

Figure 4.2(b): Main Effect Plot for mean compressive strength for w/b=0.4, Curing Period=28 days

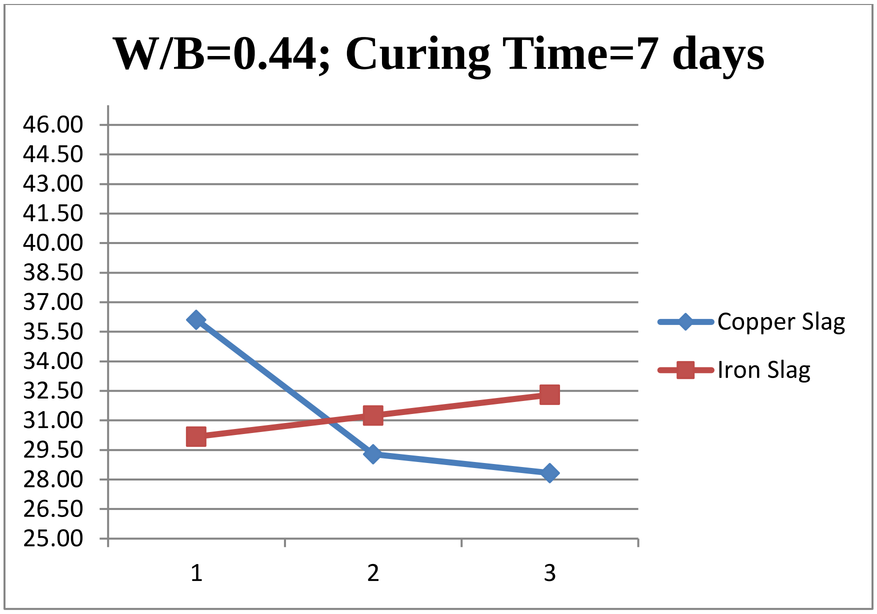

Figure 4.2(c): Main Effect Plot for mean compressive strength for w/b=0.44, Curing Period=7 days

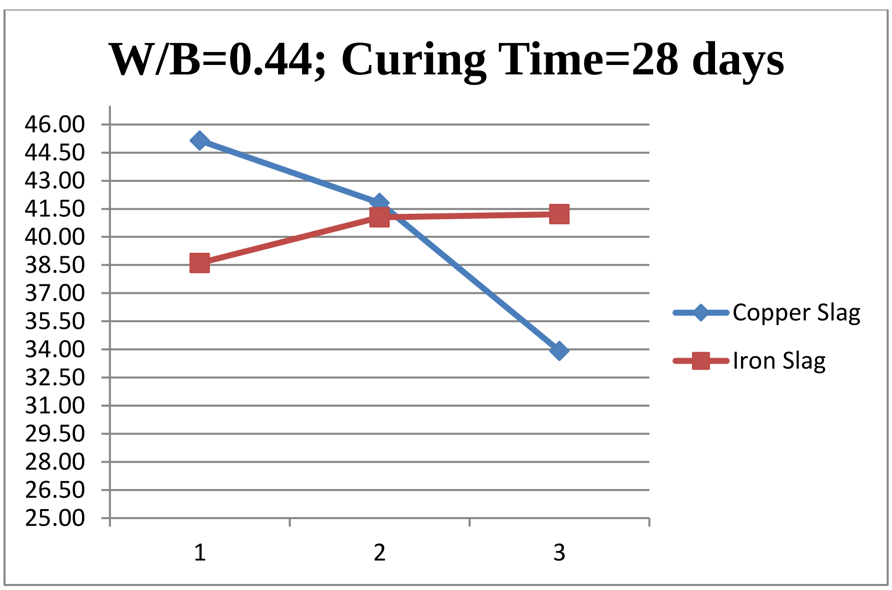

Figure 4.2(d): Main Effect Plot for mean compressive strength for w/b=0.44, Curing Period=28 days

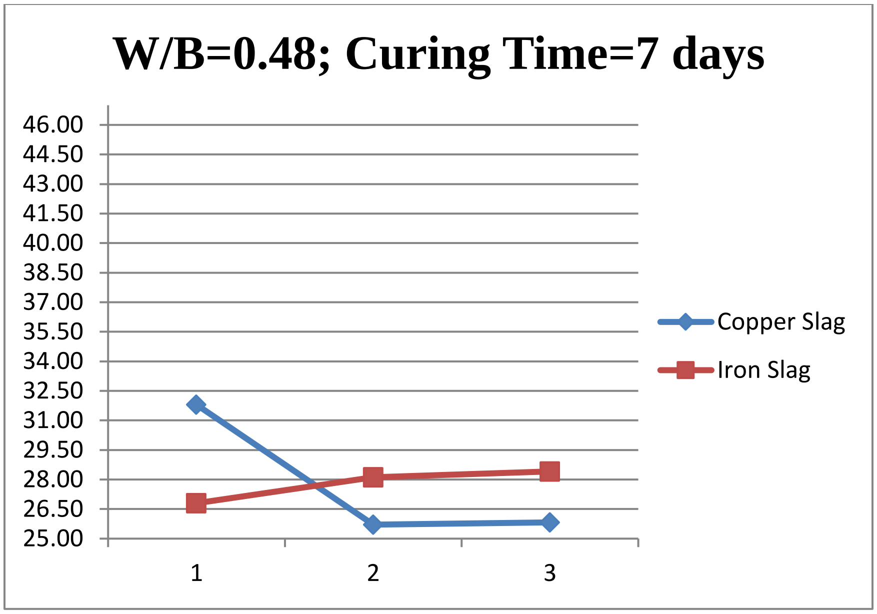

Figure 4.2(e): Main Effect Plot for mean compressive strength for w/b=0.48, Curing Period=7 days

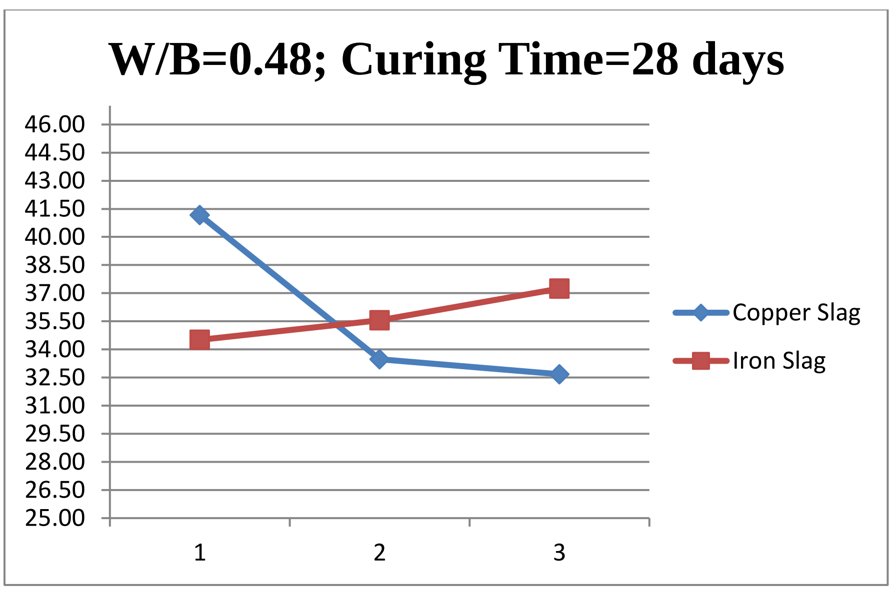

Figure 4.2(f): Main Effect Plot for mean compressive strength for w/b=0.48, Curing Period=28 days

4.4 ANOVA FOR MEAN COMPRESSIVE STRENGTH

Analysis of Variance (ANOVA) method is used to find the effect of parameters on a property and it is also helpful in knowing that if a parameter's change in level is significantly affecting a property or not. The level of significance (α) was selected as 0.05.

Table 4.4: ANOVA for mean compressive strength.

Sources of Variance	SS	d.o.f	MS	F-Value	F-Critical	Contribution (%)
W/B	178.6	2	89.30	28.68	3.08	13.65
Cement Replacement with Copper Slag	328.92	2	164.46	52.81	3.08	25.15
Fine Agg. Replacement with Iron Slag	27.75	2	13.88	4.46	3.08	2.12
Curing Time	386.4	1	386.40	124.08	3.93	59.08
Error	336.32	108	3.11			

Firstly average compressive strength corresponding to each level of sources of variance was calculated. Then sum of squares of the difference of average strength of each level to total average compressive strength was calculated, and finally the sum of square of error was calculated. Subsequent to that, the respective degree of freedom was calculated, which is one less than the total levels of each parameter. From here on the mean sum of squares was derived which is equal to sum of squares divided by d.o.f., and finally the F-value is calculated which is equal to MS of parameters divided by MS of error. Then from standard tables, F-critical value was obtained which depends upon d.o.f and level of significance. It was found that all F-values were greater than F-critical, thus showing that all the parameters were significant in the variation of compressive strength. The contribution percentage is directly proportional to F-value. Curing time was found to have highest contribution percentage and sand replacement by iron slag was found to have the least contribution.

CHAPTER 5: RESULTS & CONCLUSIONS

As described in previous chapters, effect of two parameters namely cement replacement with copper slag and sand replacement with iron slag were tested for compressive strength and analyzed by Taguchi analytical approach and ANOVA statistical method. The purpose of the ANOVA was to identify the important parameters in prediction of compressive strength.

5.1 RESULTS

From chapter 4, following results are obtained

- Control Mix CM1 with w/b ratio of 0.4 was found have the highest compressive strength of 42.1 N/mm^2 for 7 days curing and 52.9 N/mm^2 for 28 days curing.
- In case of Design Mixes with w/b ratio of 0.4, design mix DM3 with 15% copper slag replacement and 30% iron slag replacement has shown the highest compressive strength (41.2 N/mm^2 for 7 days curing period & 48.13 N/mm^2 for 28 days curing period) and highest S/N ratio (27.52 dB for 7 days curing period and 28.87 dB for 28 days curing period). It is observed that the
- In case of Design Mixes with w/b ratio of 0.44, design mix DM12 with 15% copper slag replacement and 30% iron slag replacement has shown the highest compressive strength (35.73 N/mm^2 for 7 days curing period and 45.66 N/mm^2 for 28 days curing period) and highest S/N ratio (26.28 dB N/mm^2 for 7 days curing period and 28.4 dB for 28 days curing period).
- In case of Design Mixes with w/b ratio of 0.48, design mix DM20 with 15% copper slag replacement and 20% iron slag replacement has shown the highest compressive strength (33.46 N/mm^2 for 7 days curing period and 42.13 N/mm^2 for 28 days curing period) and highest S/N ratio (25.64 dB N/mm^2 for 7 days curing period and 27.71 dB for 28 days curing period).

- All the design mixes were found to have lower compressive strength than the control mixes for respective w/b ratios.
- It is observed that in all the design mixes, compressive strength decreases with the increase in partial replacement of cement with copper slag. This may have happened due to the lower CaO content in copper slag.
- Similarly, it is observed that in all the design mixes, compressive strength increases with the increase in partial replacement of fine aggregates with iron slag. This may have happened due to presence of reactive silica and better filling of the voids.
- The highest S/N ratio for parameter cement replacement with copper slag is found to be 28.60 dB for level 1 (15% copper slag replacement), w/b ratio of 0.4 and curing time of 28 days. Delta was found to have highest value of 2.52 dB for w/b ratio of 0.44 and 28 days. This means that the size of effect of this parameter was highest for this w/b ratio and curing period.
- The highest S/N ratio value for parameter fine aggregates replacement with iron slag is found to be 27.82 dB for level 3, w/b ratio of 0.4 and curing time of 28 days. Delta was highest in case of w/b ratio of 0.4 and curing time of 7 days with a value of 0.77 dB.
- The highest mean compressive strength for parameter cement replacement with copper slag is found to be 46.78 N/mm^2 for level 1 (15% copper slag replacement), w/b ratio of 0.4 and curing time of 28 days. The highest value of delta is found to be 11.22 N/mm^2 for w/b ratio of 0.44 and 28 days.
- The highest mean strength value of parameter fine aggregates replacement with iron slag is found to be 42.90 N/mm^2 for level 3 (30% replacement), w/b ratio of 0.4 and curing time of 28 days. Delta was highest in case of w/b ratio of 0.4 and curing time of 28 days with a value of 3.4 N/mm^2.
- All factors in ANOVA i.e. w/b ratio, cement replacement with copper slag, fine aggregate replacement with iron slag, curing time were found to be significant in variation of compressive strength with variation in their levels with a significance factor of 0.05.

- Curing time was found to be the most contributing factor in compressive strength with contribution of 59.08%, on the other hand, fine aggregate replacement with iron slag was found to be the least contributing factor in compressive strength with contribution of 2.12%.

5.2 CONCLUSIONS

The following conclusions were drawn from the present study.

- It is concluded that for each w/b ratio S/N ratio for compressive strength was highest when first parameter (cement replacement with copper slag) is at level 1 (15% replacement) and second parameter (fine aggregates replacement with iron slag) is at level 3 (30% replacement).
- It is thus concluded that cement replacement with copper slag decrease compressive strength and fine aggregates replacement with iron slag increases compressive strength.
- It is concluded that all the factors affecting compressive strength are significant in variation.
- It is concluded that the most significant factor was curing time and the least significant factor was iron slag replacement of fine aggregates with contribution percentages of 59.08% and 2.12% respectively.

CHAPTER 6: REFERENCES

[1] Al-Jabri K.S., Taha R.A., Al-Hashmi A., Al-Harthy A.S., (2006). "Effect of copper slag and cement by-pass dust addition on mechanical properties of concrete." Construction and Building Materials Vol. 20 pp 322–331.

[2] Al-Jabri K.S., Hisada M., Al-Saidy A.H., Al-Oraimi S.K., (2009). "Performance of high strength concrete made with copper slag as a fine aggregate." Construction and Building Materials Vol. 23 pp 2132–2140.

[3] Al-Jabri K.S., Hisada M., Al-Saidy A.H., Al-Oraimi S.K., (2009). "Copper slag as sand replacement for high performance concrete." Cement & Concrete Composites Vol. 31 pp 483–488.

[4] Alnuaiaimi A.S., (2012). "Effects of Copper Slag as a Replacement for Fine Aggregate on the Behavior and Ultimate Strength of Reinforced Concrete Slender Columns." TJER Vol. 9, No. 2, pp 90-102.

[5] Ambily P.S., Umarani C., Ravisankar K., Prem P.R., Bharatkumar B.H., Iyer N.R., (2015). "Studies on ultra high performance concrete incorporating copper slag as fine aggregate." Construction and Building Materials Vol. 77 pp 233–240.

[6] A Guide to the Use of Iron and Steel Slag in Roads. Revision 2, (2002) Published by: Australasian Slag Association Inc.

[7] Chitra S., Kumar S.R.R.S., Chinnaraju K., Ashmita F.A., (2016). "A comparative study on the compressive strength prediction models for High Performance Concrete containing nano silica and copper slag using regression analysis and Artificial Neural Networks." Construction and Building Materials Vol. 114 pp 528–535.

[8] Dippenaar R., (2004). "Industrial uses of slag—The use and re-use of iron and steelmaking slags." VII International Conference on Molten Slags Fluxes and Salts, The South African Institute of Mining and Metallurgy.

[9] Edwin R.S., De Schepper M., Gruyaert E., De Belie N., (2015). "Effect of Copper Slag as Supplementary Cementitious Material (SCM) In Ultra High Performance Mortar

(UHPM).” Int. Conference on Sustainable Structural Concrete, 15-18 Sept 2015, La Plata, Argentina.

[10] Edwin R.S., De Schepper M., Gruyaert E., De Belie N., (2016). “Effect of secondary copper slag as cementitious material in ultra-high performance mortar.” Construction and Building Materials Vol. 119 pp 31–44.

[11] Gorai B., Jana R.K., Premchand, (2003). “Characteristics and utilisation of copper slag — a review.” Resources, Conservation and Recycling Vol. 39 pp 299–313.

[12] Hadiwidodo Y.S., Mohd S.B., 2010. “Taguchi Experiment Design for Investigation of Freshened Properties of Self-Compacting Concrete.” Am. J. Engg. & Applied Sci., Vol.3 No.2 pp 300-306.

[13] Humam T., Siddique R., (2013). “Properties of Mortar Incorporating Iron Slag.” Leonardo Journal of Sciences Vol. 23 pp 53–60.

[14] IS: 10262-1982 (Reaffirmed 2004): Recommended guidelines for concrete mix design, Bureau of Indian Standard, New Delhi-2004.

[15] IS: 383-1970: Specification for Coarse and Fine Aggregates from Natural Sources for Concrete, Bureau of Indian Standard, New Delhi-1970.

[16] IS: 2386 (Part I, III)-1963: Methods of Test for Aggregates for Concrete, Bureau of Indian Standard, New Delhi-1963.

[17] IS: 4031 (Part 4, 5&6)-1988: Methods of Physical Tests for Hydraulic Cement, Bureau of Indian Standard, New Delhi-1988.

[18] IS: 8112-1989 (Reaffirmed 2005): Specification for 43 Grade Ordinary Portland Cement, Bureau of Indian Standard, New Delhi-2005.

[19] Khajuria C., Siddique R., (2014). “Use of Iron Slag as Partial Replacement of Sand to Concrete.” International Journal of Science, Engineering and Technology Research (IJSETR), Volume 3, Issue 6 pp 1877–1880.

[20] Khanzadi M., Behnood A., (2009). “Mechanical properties of high-strength concrete incorporating copper slag as coarse aggregate.” Construction and Building Materials Vol. 23 pp 2183–2188.

[21] Kumar M.P., Mahesh Y., (2015). “The Behaviour of Concrete by Partial Replacement of Fine Aggregate with Copper Slag and Cement with GGBS —An Experimental Study.” IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE) Volume 12, Issue 3 Ver. III, pp 51–56.

[22] Li Z., Zhao S., Zhao X., He T., (2013). “Cementitious property modification of basic oxygen furnace steel slag.” Construction and Building Materials Vol. 48 pp 575–579.

[23] Li Q., Ding H., Rahman A., He D., (2016). “Evaluation of Basic Oxygen Furnace (BOF) material into slag-based asphalt concrete to be used in railway substructure.” Construction and Building Materials Vol. 115 pp 593–601.

[24] López M.M., Pineda Y., Gutiérrez O., (2015). “Evaluation of durability and mechanical properties of the cement mortar added with slag blast furnace.” Procedia Materials Science Vol. 9 pp 367–376.

[25] Mirhosseini S.R., Fadaee M., Tabatabaei R., Fadaee M.J., (2017). “Mechanical properties of concrete with Sarcheshmeh mineral complex copper slag as a part of cementitious materials.” Construction and Building Materials Vol. 134 pp 44–49.

[26] Moura W.A., Gonçalves J.P., Lima M.B.L., (2007). “Copper slag waste as a supplementary cementing material to concrete.” J Mater Sci 42:2226–2230.

[27] Najimi M., Sobhani J., Pourkhorshidi A.R., (2011). “Durability of copper slag contained concrete exposed to sulfate attack.” Construction and Building Materials Vol. 25 pp 1895–1905.

[28] Ouda A.S., Abdel-Gawwad H.A., (2015). “The effect of replacing sand by iron slag on physical, mechanical and radiological properties of cement mortar.” Housing and Building National Research Center Journal.

[29] Ozbay E., Erdemir M., Durmuş H. İ., (2016). “Utilization and efficiency of ground granulated blast furnace slag on concrete properties – A review.” Construction and Building Materials Vol. 105 pp 423–434.

[30] Patnaik B., Sekhar S., Rao S., (2015). “Strength and durability properties of copper slag admixed concrete.” IJRET: International Journal of Research in Engineering and Technology Vol. 4 pp 158–166.

[31] Prasad P.S., Ramana G.V., (2016). “Feasibility study of copper slag as a structural fill in reinforced soil structures.” Geotextiles and Geomembranes Vol. 44 pp 623–640.

[32] Santamaría A., Orbe A., Losañez M.M., Skaf M., Ortega-Lopez V., González J.J., (2017). “Self-compacting concrete incorporating electric arc-furnace steelmaking slag as aggregate.” Materials and Design Vol. 115 pp 179–193.

[33] De Schepper M., Verlé P., Driessche I.V., De Belie N., (2015). “Use of Secondary Slags in Completely Recyclable Concrete.” J. Mater. Civ. Eng., 2015, 27(5): 04014177.

[34] Shi C., Meyer C., Behnood A., (2008). “Utilization of copper slag in cement and concrete.” Resources, Conservation and Recycling Vol. 52 pp 1115–1120.

[35] Singh G., Siddique R., (2016). “Strength properties and micro-structural analysis of self-compacting concrete made with iron slag as partial replacement of fine aggregates.” Construction and Building Materials Vol. 127 pp 144–152.

[36] Singh J., Singh J., Kaur M., (2014). “Use of copper slag in concrete.” International Journal of Advanced Research in Engineering and Applied Sciences Vol. 3 No. 12.

[37] M. Sudarvizhi S., Ilangovan. R (2011). “Performance of Copper slag and ferrous slag as partial replacement of sand in Concrete.” International Journal of Civil and Structural Engineering Vol. 1, No 4 pp 918–927.

[38] Wu W., Zhang W., Ma G., (2010). “Optimum content of copper slag as a fine aggregate in high strength concrete.” Materials and Design Vol. 31 pp 2878–2883.

[39] Hadiwidodo Y.S., Mohd S.B., 2010. Taguchi Experiment Design for Investigation of Freshened Properties of Self-Compacting Concrete. Am. J. Engg. & Applied Sci., 3(2): 300-306

[40] Olivia M., Nikraz H., 2012. Properties of fly ash geopolymer concrete designed by Taguchi method. Materials and design 36, 191-198.

[41] Ozbay E., Oztas A., Baykasoglu A., Ozbebek H., 2009. Investigating mix proportions of high strength self compacting concrete by using Taguchi method. Construction and building materials 23, 694-702.