OPTIMIZATION OF CONCRETE MIX DESIGN USING STATISTICAL METHODS

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In

Structural Engineering

Submitted by

Purnima

Roll. No. 801624021

Under the supervision of

Dr. Sahil Bansal

Assistant Professor, CED

THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

Department of Civil Engineering

Thapar Institute of Engineering and Technology, Patiala

India

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DECLARATION

I Purnima, hereby declare that the work presented in this thesis entitled "**Optimization of Concrete Mix Design Using Statistical Methods"** in partial fulfilment of the requirement for the award of degree of Master of Technology (Structural Design) submitted at Civil Engineering Department , Thapar Institute of Engineering & Technology (Deemed to be University), Patiala is an authentic record of work carried out under supervision of Dr. Sahil Bansal, Assistant Professor, CED, Thapar Institute of Engineering & Technology (Deemed to be University), Patiala. The matter presented in this has not been submitted either in part or full to any other university or institute for the award of any other degree.

Date: 25/07/2018

(Purnima)

(801624021)

It is certified that the above statement made by the student is correct to the best of my knowledge and belief.

Date: 25/07/2018

25/7/18

Dr.Sahil Bansal,

Assistant Professor, CED,

Civil Engineering Department

Thapar Institute of Engineering & Technology

(A Deemed To Be University), Patiala, Punjab

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ABSTRACT

Concrete is the most essential part of the civil engineering projects. Optimization of the concrete mix design is motivated by the ever- increasing need of the designers to proportion the concrete mixtures that are able to satisfy the multiple performance necessities. Purpose of the current work is to develop a model that is capable of reproducing a concrete strength between 60MPa to 90MPa within a specific range of cement content, fly ash content, silica fume content and cost. The model can generate data on mix proportions and their corresponding compressive strength and slump, thereby, providing useful information safe and ready-to-use mix designs.

21 mixes of strengths 60MPa, 65MPa…..90MPa and 3 required slumps i.e. 50mm, 80mm and 120mm were designed and casted (100x100x100 mm cubes) with 4 replicas of each. Regression analysis was carried out on the experimental data and mathematical equations for strength and slump were developed. The two equations so developed along with 11 other constraints were then used to develop a optimization model using MATLAB optimization tool.

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CHAPTER 1

INTRODUCTION AND STATEMENT OF ANALYSIS

1.1 GENERAL

The most extensively used construction material in the world is 'concrete'. This is because of its flowability in most complicated fashion i.e. the capability to take any shape when in wet condition, and its strength gaining characteristics when in hardens. Generally, concrete is used to build protective structures, which are subjected to considerable stress conditions. Concrete is therefore, the most widely used construction material manufactured at the site. Concrete is the most largely produced synthetic material on earth. It is a composite material as it is obtained by mixing aggregates and cement with water. Manufacturing includes a number of operations according to prevalent site conditions. The ingredients of extensively varying characteristics can be used to produce concrete of obligatory quality. The durability, strength, workability and various other characteristics of concrete depend upon the attributes of its ingredients, the proportions of the mix, the method of compaction and other processes and controls. Concrete is so much popular as a material for construction because of the fact that it is built from commonly available ingredients and can be altered to functional requirements in a peculiar situation. Among all the properties of concrete, its compressive strength and workability are crucially important. They both play an equally important role in the mix design of concrete. Other factors such as water cement ratio, specific gravity of cement and fineness modulus of aggregates have their own importance in mix design. With the remarkable property of cement and water, converting a pile of aggregates into rock in just a few hours, seems to be no other material that could take over concrete in the forthcoming future to meet our societies' customary needs for infrastructure, housing and protection.

Figure 1.1: Basic constituents of concrete

Due to the extensive use of concrete, the application of cement has reached approximately 10 billion metric tons per year [1]. Cement is the main component that controls the strength of the concrete. Minimum cement content is always specified that may reach the desired strength and durability but sometimes more than the required is observed to be used. This exaggerated amount of cement should be minimized to prevent its adverse effect on cost of concrete as well as environment because:

i. Cement is the most expensive component in concrete.
ii. Cement production vents approximately 5% of global energy consumption and 5% of global carbon dioxide (CO_2).
iii. It contributes of about 90% CO_2 burden of a concrete mixture.

Today, almost all the countries are observing a rapid growth in the construction industry which involves the use of natural resources for the development of the infrastructure. This growth is endangered by the deficiency of the natural resources that are available. Natural resources are depleting worldwide along with which new by products are being generated by various industries which can have a propitious future in construction industry as partial or full replacement of either cement or aggregates. In the last few decades there has been a rapid increase in the waste materials and by-products production due to the great increase in the population, development of industry and technology and the growth of consumerism. Further, the dumping of the waste materials is a big issue as they have environmental effects on the soil and landscape as well as social and economic impacts. Moreover, they can degrade over time and may be source of toxic metals [2]. Therefore, cement replacement with some other cementitious material is a smart idea and also the need of the hour. There are many materials available for this, such as fly ash, silica fume, copper slag, iron slag etc. However, the prime choice which material should be taken and how their proportioning in concrete mix design should be done is not well known. The source of production of fly ash is the burning of coal (powdered) or some of other materials. It can be seen in the form of dark flecks carried in the air. Silica fume, an ultrafine powder collected as a by-product from the silicon and ferrosilicon alloy production and consists of spherical particles. They have an average particle diameter of 150 nm. Both of these materials have pozzolana properties and therefore can be used for partial replacement of cement.

1.2 PROBLEM IDENTIFICATION AND OBJECTIVES

In order to obtain good quality of concrete, the constituents must be proportioned properly. Mix design for concrete, also called as mix proportioning is a process of search for a mixture fulfilling the necessary performance of concrete, mainly workability, strength and durability. The proportioning also depends on the application of the concrete.

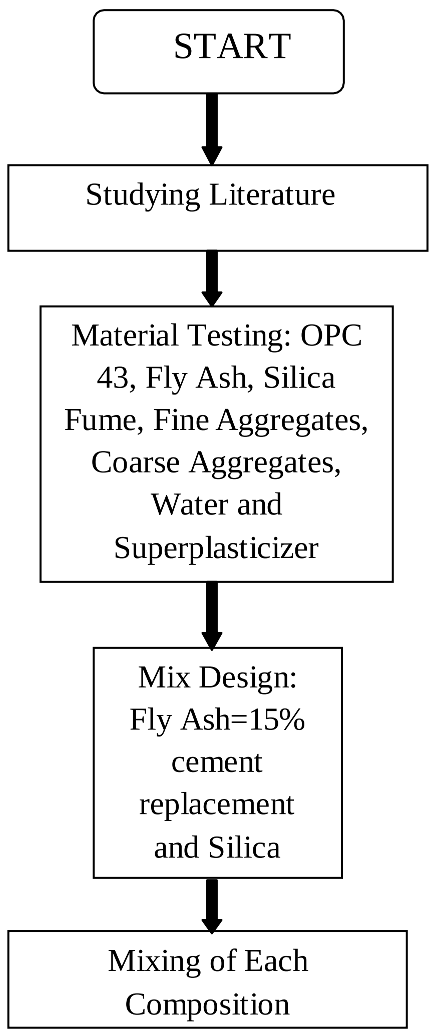
Optimization of the concrete mixture design is a process of search for a mixture for which the sum of the costs of the ingredients is lowest, yet satisfying the required performance of concrete, such as workability, strength and durability. The basic ingredients of concrete can be classified into two 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 [3] and also by increasing the aggregate/cement ratio [4]. Goltermann et al. 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 [5].

Attempts have been made in the past to optimize the concrete mixture design using the fully experimental methods or fully analytical methods or semiexperimental (half-analytical) methods or statistical methods. Fully experimental methods 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 [6]. 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 [7]. Analytical methods 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. Semiexperimental (half-analytical) 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. Statistical methods, also termed as statistical experiment design methods or statistical factorial design methods or design of experiments methods or empirical methods, are also used frequently in obtaining the optimum concrete mixture design [8]. Statistical 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 pozzolana replacement. After a response can be characterized by an equation (model), several analyses are possible. For example, a user could determine which mixture proportions would yield one or more desired properties. A user also could optimize any property subject to constraints on other properties. Simultaneous optimization to meet several constraints is also possible. For example, one could determine the lowest cost mixture with strength greater than a specified value, air content within a given range, and slump within a given range.

Fully analytical methods are less expensive and less time consuming but they have the disadvantage of being less precise because of the variations in the materials characteristics of the aggregates and cements. Fully experimental or semiexperimental (i.e., half-analytical) methods are reliable and accurate; however, they involve comprehensive laboratory works [9]. Statistical methods also require a certain amount of experimental works but they have an additional advantage so that uncertainty helps in the characterization of expected properties upto a significant extent

1.3 SCOPE OF WORK AND WORK METHOD

In the present work, an effort has been made to exhibit the Statistical method to obtain optimum proportioning of concrete mixtures containing fly ash and silica fume using the data obtained through an experiment design considering water binder ratio, binder content, and fine over total aggregate ratio as design factors. The experimental data is then analyzed statistically and mathematical polynomials regression is developed for concrete strength as a function of mixture variables. The utility of the developed compressive strength and slump model in optimizing the mixture designs is illustrated considering different possible options.



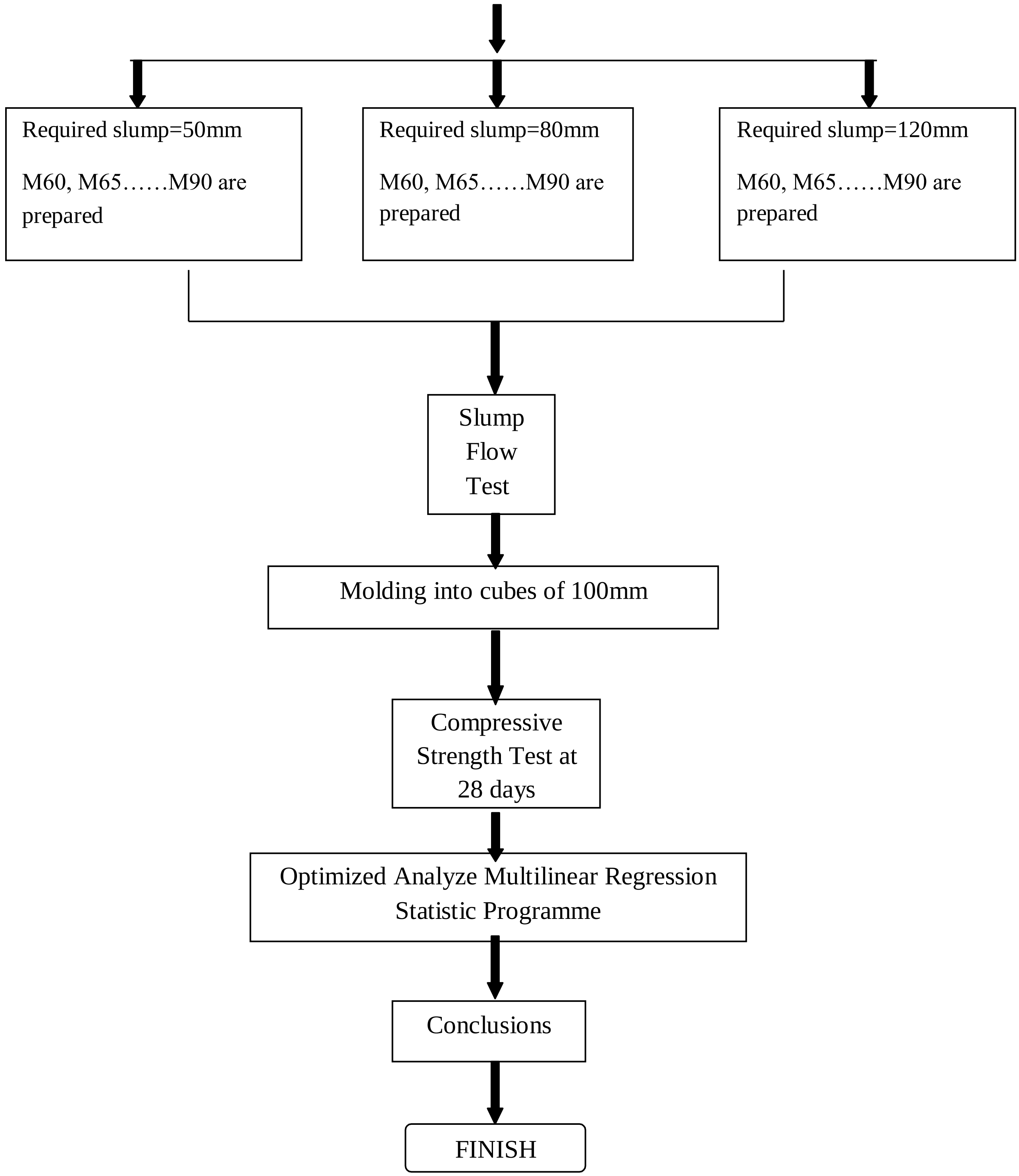


Figure 1.2: Workflow chart to produce optimum mix design

1.4 ARRANGEMENT OF THESIS

Chapter 1 presents the brief introduction of the complete dissertation including the statement of problem and objectives of the complete research work.

Chapter 2 describes in brief the literature work on various methods of optimization of concrete mix design.

Chapter 3 presents the ingredients of the concrete used in the present work and also the importance of the various ingredients. It also presents the method of concrete mix design used in this work.

Chapter 4 explains in detail the method of optimization that has been used i.e. the statistical method and also the knowledge of the regression analysis.

Chapter 5 displays the experimental program and the effect of various properties on compressive strength and slump of the concrete.

Chapter 6 demonstrates the conclusion drawn from the work done so far and future scope of the work.

CHAPTER 2

LITERATURE REVIEW

2.1 ARTIFICIAL NEURAL NETWORK (ANN)

2.1.1 Introduction to ANN

A neural network model is basically a computer model and the functioning of which is based upon the learning power of the human brain. The processing elements of a neural network comprise of many simple computational elements that are arranged in layers plus they are similar to the neurons in the brain. The output may is passed on to other neurons. The learning process generally involves determining the connection weight matrices representing the relationship nested in the training data. The network grasps by comparing its output for each input pattern with a target output for that pattern, then calculating the error and propagating an error function backward through the net. Once the training is done, the values for the project input parameters are presented to the network. Then, on the basis of the existing weight values and thresholds (from the training process), the network calculates the node outputs. The degree of accuracy in this generalization is dependent upon the comprehensiveness of the training set [10].

Experimental data from various sources is collected to produce a learning set and also to check the reliability of the models (strength and slump). These sources may be our own experiments performed in the laboratory or the literature work of various authors. Random sampling is utilized to shuffle all the records and break them into 2 sets i.e. training set and testing set. The training set is explained above; the testing set is kept untouched. It is used to compare the output of the ANN and the values of the testing set.

2.1.2 Methodology and Equations Used

The following three steps formulate the methodology of the procedure [11]:

1. Modeling: It builds an accurate model for compressive strength and workability using artificial neural networks and experimental data.
2. Incorporating: It incorporates the models (formed above) in software which grants an evaluation of the specified properties for a given mix.

3. Optimizing: It incorporates the software results into a nonlinear programming package which further grants a search for the optimum proportion of the concrete mix design.

2.1.3 Literature for ANN

I-Cheng Yeh (1999) - Design of high-performance concrete mixture using neural networks and nonlinear programming

The author has followed the ANN approach with an addition of using a computer based software named as HPC2N (High Performance Concrete Design Package Using Neural Network and Nonlinear Programming) for performing optimum concrete mix design based on the proposed methodology. The basic 3 steps are followed viz. modeling, incorporation and optimization. All the above mentioned equations were also kept in mind while developing the architecture. Modeling for strength and slump was done separately. After this the optimization was done using HPC2N [12] and then experimental data was also set to compare the optimized results with the predicted values.

Following 2 things were observed:-

1. An increasing required strength increased the content of cement, slag, SP, and coarse aggregate and reduced the content of water and fine aggregate, while the content of fly ash was not much affected.

2. An increasing required workability increased the content of cement, slag, water, and SP and reduced the content of fine aggregate, while the content of fly ash was not much affected.

I-Cheng Yeh (2009) - Optimization of concrete mix proportioning using flattened simplex-centroid mixture design and neural networks

In this paper an attempt has been made to combine the 3 technologies, i.e. Design of experiments (DOE), Artificial Neural Networks (ANN), Mathematical Programming (MP).The DOE and ANN reduce the number of trials whereas the MP optimizes the mixture to lower cost. Both of these objectives are reached without sacrificing the desired compressive strength and workability. 127 mixtures were initially planned to be taken but later 78 mixtures were kept neglecting the others (impractical combinations). The compressive strength varied from 25 to 55 MPa and the slump from 5 to 25 cm. Flattened simplex centroid method was adopted to adjust the SP content. Compressive strengths were recorded for each of the 78 mixtures. This data was used to develop a Neural Network which could be further used to optimize the concrete mixtures.

Using a training process, a training set is finalized. This set calculates the node outputs. Input layer-7 thing (cement, fly ash, slag, water, SP, CA, FA) and Output layer- 2 things (compressive strength and slump).

2.2 GENETIC ALGORITHM

2.2.1 Introduction to Genetic Algorithm

A new design method for concrete mixture designing using genetic algorithm to minimize the number of trials and provide approximate mix proportions is discussed in this section. The initial set of random solutions is called as the Population; each individual in the population is called as a Chromosome (solution to the problem). The evolution from the initial data to the optimized data is similar to the process of Darwinian evolution process to create population from one generation to another.

The general procedure of genetic algorithm includes the following sequence:

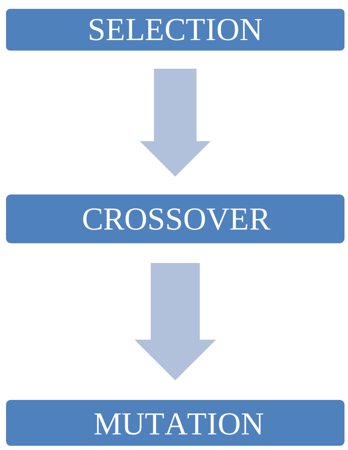


Figure 2.1: Sequence of Genetic Algorithm.

2.2.1.1 Selection

The driving force in genetic algorithm is provided by the "selection". In general cases, a low selection pressure is recommended in the early stages of genetic algorithm, when in search of a wide exploration of the search space, while high selection pressure is suggested at the end. The purpose of this is to attain the most promising regions in the search space.

Further, there are three ways in which selection can be done.

1. Proportional selection

2. Ranking Selection

3. Tournament Selection

Come what may be the selection process, survival probability for each chromosome proportional to the fitness value is critical.

2.2.1.2 Crossover

Crossover simulates the sexual generation of a child from two parents. This is performed by taking parts of the bit string of one of the parent whereas, some other parts from the other parent and finally combining both the parts in offspring [13]. The ratio of the number of the offspring produced to the population size (in each generation) is defined as the crossover rate. This ratio controls the expected number of chromosomes to undergo the crossover. There are three kinds of crossover:

i. Single-point (only one random cut is made)

ii. Two-point (two random cuts are made)

iii. Uniform crossover (firstly, it generates a random crossover mask and then it exchanges relative genes between parents)

2.1.1.3 Mutation

The percentage of new genes to the total number of genes in the population is defined as the mutation rate. It controls the rate at which the new genes are introduced into the population for trial. If it is too slow, many genes are never tried out (that would have been helpful). But if it is too high, there will be much random perturbations, the offspring will start losing their resemblance to the parents and the algorithm will lose the skill of gaining from the history of the search.

By repeating the process of selection, crossover and mutation, the fitness can be increased. When the desired fitness is achieved, the repeating process is terminated.

Further, multiple regressions are used to achieve the fitness functions. If the fitness is greater than 70%, only then the set is kept and considered to be optimum otherwise it is discarded.

A set of experimental data (from the literature or laboratory) and a set of data from the genetic algorithm are compared, errors are found.

2.2.2 Literature for Genetic Algorithm

Chul-Hyun Lim et al. (2004) - Genetic algorithm in mix proportioning of high-performance concrete

In this paper, the author initiated the work with the basic 3 steps of genetic algorithm i.e. selection, crossover and mutation. The process is repeated till we reach to a fitness value. To achieve this, we go for multiple regressions. Two fitness function for compressive strength (one for compressive strength between 40-80MPa and the other between 80-120MPa) and two for slump are recognized. Only the data with fitness function>70% is kept from the selection data set i.e. they are considered to be fit.

The fitness functions are as follows:-

Table 2.1: Fitness Functions for Compressive Strength and Slump [13]

COMPRESSIVE STRENGTH FUNCTION	40-80MPa(low strength range)	80-120MPa(high strength range)
	f_c'=122.14 - 0.84w/b - 0.42W+0.34s/a-0.09 FA + 363.77 AE	f_c'=170.33 – 1.87w/b - 0.51W + 1.2s/a - 0.49SF
SLUMP FUNCTION	Slump=(-463.21) – 3.05w/b + 5.21W + 0.54 s/a + 0.11 FA – 6541.17 AE + 41.67 SP	Slump=-387.01 + 16.94w/b + 0.58W – 1.23s/a -0.377SF + 1.163SP

After this 181 finally selected mixtures (fit) were compared with the 25 mixtures (from the literature work) and errors were calculated.

I-Cheng Yeh (2007) - Computer-aided design for optimum concrete mixtures

In this paper, the modeling is done with the help of neural networks and the optimization of the design is done with the help of non-linear programming and genetic algorithm. The input for the neural network includes certain constraint equations [14], unit weight of the concrete components and unit cost of the concrete components. The outputs involve slump and strength, optimized compressive contents, calculated component ratio and optimized cost.

2.3 STATISTICAL METHOD

2.3.1 Introduction to Statistical Methods

A statistical model formalizes a relation between variables. It explains how one or more variable is related to one variable. These methods aim to advance the experimental methods, in which, instead of selecting one starting mix proportion and then adjusting them by trial and error method, we achieve an optimized solution by statistical modeling.

A set of trail batch is defined such that it covers a range of proportions. The test specimens are fabricated tested and results from the experimental works are analyzed using the standard statistical tools. The models include fitting of the empirical models to the data for each performance criteria. In these models, each response i.e. the resultant concrete property is expressed in the form of algebraic function of various factors (on which the property is dependent) such as w/c ratio, %age cement replacement, FA/TA ratio. After a response is characterized by the mathematical models, various analyses become feasible.
They come under the category of semi experimental method and are quite reliable. They also involve sufficient amount of laboratory work. At the same time, they have an additional benefit of seeing the expected properties (responses) can be characterized by variability i.e. uncertainty. They are suitable for producing cost-effective concrete mixture.

2.3.2 Literature for Statistical Methods

M. Shariq et al. (2012)-Optimization of concrete mix proportioning.
The author's main objective is to study the influence of various factors in concrete mix proportioning, to develop statistical model from experimental data and to optimize the mix the proportioning for available material and conditions.64 mix cubes were designed and casted on the basis of selected previous literature work. They had different water cement ratio, coarse to total aggregate ratio, total aggregate to cement ratio and their thorough compressive strengths were measured. They were then compared with the already calculated strengths from the previous literature taken as the basis of the 64 mixes. Regression analysis was carried out and the equation of strength was obtained. Also, the graph between the measured and computed strengths was plotted and it was seen that there was a good agreement between the two.

Table 2.2: Finalised values

Water to cement ratio	Compressive strength	Total aggregate to cement ratio
0.45	45	4.4
0.5	35	5.1
0.55	25	5.7

M.A. DeRousseau et al. (2018) -Computational design optimization: A Review

According to the review work of this author, the experimental design of the concrete mix cannot be generalized due to the variability in the constituent characteristics and environmental conditions. So, the author focuses on the computational design optimization of concrete mixtures which include 3 steps i.e. formulation of the problem, modeling and solving of the optimization problem. Various types of modeling like linear, life cycle etc are given with specialty of each of them for example- the linear model is best for cost optimization. Similarly, the various methods of optimization are also listed. One can choose any of them according to the work's requirement. Future trends in the concrete mix design optimization have also been discussed.

Shamshad Ahmad et al. (2014) - A statistical approach to optimizing concrete mix design

A step by step statistical approach for the optimization of concrete mix design has been proposed in this paper. The trial mixes were considered on the basis of full factorial experiment design. A total of 27 mixes with each having 3 replicates were prepared. 81 mixes were then casted and their 28 day compressive strength was measured. ANOVA was carried out on the experimental data and then regression model for the same was developed. It was a 5 step approach. Also, the effect of w/c ratio and FA/TA on the compressive strength was studied. The optimum values of the above two ratios resulted in higher strength and the low cementitious materials resulted in significant cost saving in the manufacture of concrete.

Alizeri Habibi et al. (2018) - Development of an optimum mix design method for self-compacting concrete based on experimental results

Optimization of the cost and compressive strength of the self compacting concrete are the two major objectives of the author in this paper. According to the author, the aim can be achieved if the aggregate sizes are chosen effectively and if the optimization of the mix is carried out without adding additives. 42 mix designs were prepared, each with 3 replicates i.e. 126 cube specimens were casted and tested for 28 day compressive strength. Mix design optimization problem was developed and after solving the problem, optimal mix design for cost and compressive strength was developed. Also, the final results were examined and compared with some recent literature. The results of the proposed method came out to be better than some previously proposed methods.

CHAPTER 3
CONCRETE MIX DESIGN

3.1 GENERAL

The present chapter discusses the conventional method of mix proportioning of concrete. It is the process of selecting appropriate ingredients of concrete and deciding their optimum quantities which would generate concrete that would satisfy the job's essential requirements.

3.2 PRINCIPLES OF CONCRETE MIX DESIGN

The concrete mix proportioning comprises of resolving the relative quantities of constituents of constituents of the concrete for its production for a given purpose. The process of the choosing of constituent is called as the "Concrete Mix Design" and is completely different from structural design. The proportioning may be based empirical data; data obtained from literature etc. considering the properties, amounts and costs of ingredients is inclusive of the process. Also, the requirements of placing and finishing of fresh concrete and properties of the hardened concrete such as strength etc are to be studied in this process.

Aim of the concrete mix design shall be:

i. Satisfying the requirements of fresh concrete i.e. slump requirements.
ii. Strength and durability- satisfying the hardened concrete properties.
iii. Performing most optimally under the given environmental condition in the structure.

In addition to the above mentioned requirements, the cement content must be kept as minimum as possible to attain maximum economy. Therefore, the ingredients of the concrete are to be proportioned vigilantly because this part of the concrete technology ensures the good quality and economy of the concrete.

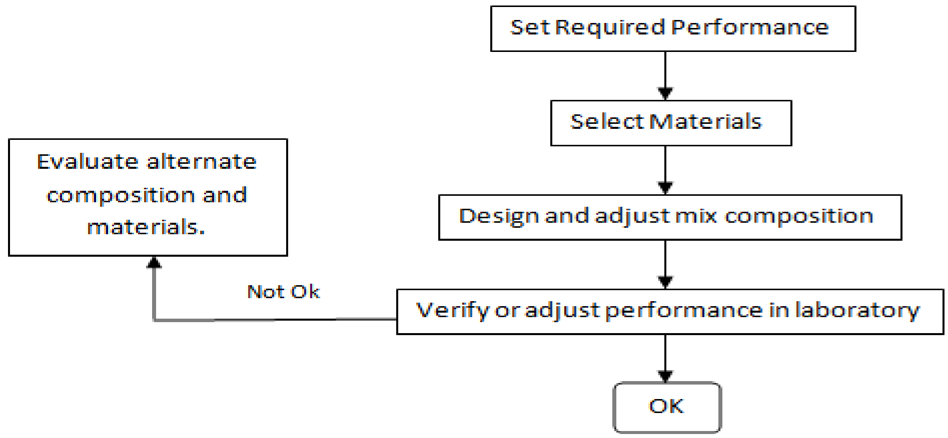


Figure 3.1: Flowchart for mix design and casting

3.3 INGREDIENTS OF CONCRETE MIX

i. Cement
ii. Aggregates (fine aggregates and coarse aggregates)
iii. Water
iv. Supplementary Cementitious Materials (silica fume and fly ash)
v. Superplasticizer (SP)

3.3.1 Cement

Cement is a water-based binder used to bind other building materials together. The binding occurs only when water reacts with cement. Eventually, a stone like material is formed. The chemical process of cement reacting with water is called as hydration. Cement fills up the voids present in fine aggregates, making the concrete impermeable. Additionally, it tenders strength to the concrete on setting and hardening.

3.3.2 Aggregates

They comprise of the largest volume of the concrete and divided into two categories (given below).

- <u>Coarse Aggregates</u>: It is the strongest component of concrete and its selection depends upon numerous properties like crushing strength, durability, flakiness, maximum size and occurrence of deleterious particles. The size of selection is dependent upon two factors;

first, bigger the particle size, more is the stress concentration around the particles because of the difference between the modulous of paste and aggregates, leading to the failure of bond between mortar paste and aggregates. Second, the crushing process is likely to take place along the zone of weakness contained by the parent rock and removes them. Therefore, smaller sized particles are deemed to be stronger than the bigger ones [15].

- Fine Aggregates: Rounded shaped and smoothed textured fine aggregate particles are expected to entail less water for mixing process. If the fineness modulous (FM) is less than 2.5, stickiness is likely to be introduced into the concrete, triggering difficulty in its compaction. However, FM of about 3 is prone exhibit best workability and compressive strength results. In order to have minimum void ratio, sand particles should be packed properly failing to which, requirement of water increases. To conclude, sand should be free from clay, silt, chlorides etc.

3.3.3 Water

Generally, water fit for drinking purpose is also satisfactory for fabrication of concrete. Technically, water that conforms to the requirements of IS: 456 are considered to be robust for the production of concrete mix.

For the mixing, the water quantity is set to a least level that corresponds to the hydration of cement; excess to this instigates void formation in the concrete's hardened cement phase. Impurities like sulphates, carbonates, chlorides etc negatively affects the setting characteristics of concrete. Also, they bring about reduction in initial and final strengths. The salt content in water should also be limited as it affects the hydration rate of cement. If the above point is ignored, higher amounts of heat of generated which further leads to the decreased amount of water and subsequent loss of workability. The maximum allowable chloride content is given in IS: 456-2000, Table 7.

Water content is also influenced by the following factors:-

- Aggregate size
- Shape
- Workability
- w/c ratio

- exposure conditions
- other SCM properties

3.3.4 Supplementary Cementitious Materials (SCM)

In the recent years, the use of SCM has increased, partly for the reasons of economy and partly because of the technical benefits accounted by the materials [16]. In case of High Strength Concrete, they are used for even stronger reasons.

- Silica Fume: Silica fume (very fine non-crystalline silicon dioxide) is a by-product of the concoction of silicon, ferrosilicon or the like, from quartz and carbon in electric arc furnace. SF conforming to a standard approved by the deciding authority can be possibly used as part replacement of OPC, provided uniform blending with cement is confirmed. It is usually advantageous in proportion of 5 to 15 percent of the cement content of a mix [17].
- Fly Ash (Pulverized fuel ash): It is grey in colour and alkaline in nature and is a by-product from the combustion of coal in thermal power plants. Fly ash conforming to Grade I of IS 3812 may be used as part replacement of OPC. Uniform blending with cement has to be taken care of.

3.3.5 Superplasticizer (SP)

SP are also called as high range water reducing admixtures as they have the capability to decrease the water by three to four times [18], which is higher than any normal water reducing admixture. Therefore, superplasticizers allow the production of concrete with dropped water content without negotiating workability, opening the doors to radical upgradations in concrete performance.

3.4 DESIGN METHODS

The design methods that are trailed around the world are almost similar. Only slight disparities are observed in various design methodologies in the process of choosing the mix proportions. Common design methods are:-

- Mix Design According to Indian Standard Recommended guidelines

- Trial and Error Method
- British Mix Design Method
- ACI Mix Design method
- USBR Mix Design Method

In the present work Mix Design According to Indian Standard Recommended guidelines has been used for working out the mix design data. The IS Code design method has been conferred briefly in the subsequent paragraphs.

3.5 MIX DESIGN ACCORDING TO THE INDIAN STANDARD RECOMMENDED GUIDELINES (IS: 10262)

The design of the mixtures were done according to the guidelines stated in the IS Code 10262 [19].

A simplified procedure for the mix proportioning of mixes greater tha 60MPa compressive strength is given in the following steps:

1. Target strength of mix proportioning is found by the equation:

   $f'_{ck} = f_{ck} + 1.65\ S$ equation (3.1)

   $f'_{ck} = f_{ck} + X$ equation (3.2)

   Choose whichever is higher from equation (a) and (b)

   where,

   f'_{ck}= target mean compressive strength at 28 days in N/mm^2

   f_{ck}= characteristic compressive strength at 28 days in N/mm^2

   S= standard deviation in N/mm^2 (see Table3.1)

   X= a factor based on the grade of concrete (see Table3.2)

2. The selection of the maximum size of aggregates is generally bounded to 20mm but for mixes with 80 MPa and above, the maximum size has to be constrained between 10mm and 12.5mm.

3. Selection of water content is done according to the Table3.3. Also, the water content varies if the required workability is high. Variations can be done according to the trial mix slump test results. Similarly, the SP quantity has to be fixed after various trial batchings and the required slump. The water so finalized has to be reduced by the use of HRWRA according to IS: 9103.

4. The w/c ratio selected according to Table 3.4 which recommends the w/c values as a function of maximum size aggregates to achieve the different target compressive strength at 28 days. Also, these values are for concrete incorporated with silica fume and HRWRA. If fly ash is also used, the cementitious material content shall be suitable increased and w/c hall be recalculated in accordance with the total cementitious materials used.
5. The cementitious materials content is calculated from the quantity of water. The minimum and maximum limits on the cementitious materials' content as per IS:456 (2000) has to be conferred. Table3.5 shows the limit on pozzolanic materials' content.
6. After the absolute volume of binder, water and the chemical admixture is found, divide their mass by their respective specific gravity, divide by 1000 and subtract the result of their summation from unit volume. Further, the values so attained are divided into coarse and fine aggregate fractions by volume in accordance with coarse aggregate proportion determined from Table3.6. Lastly, the coarse and fine aggregate contents are calculated by multiplying with their respective specific gravities and multiplying by 1000.

Table 3.1: Assumed Standard Deviation(S)

Concrete Grade (N/mm^2)	Assumed Standard Deviation (N/mm^2)
M10 M15	3.5
M20 M25	4.0
M30 M35 M40 M45 M50 M55 M60	5.0

M65 M70 M75 M80	6.0

Table 3.2: Value of X

Concrete Grade (N/mm^2)	Value of X
M10 M15	5
M20 M25	5.5
M30 M35 M40 M45 M50 M55 M60	6.5
M65 and above	8

Table 3.3: Water Content per Cubic Metre of Concrete as per IS Code 10262

Nominal Size of Aggregate (max.) (mm)	Water Content (max.) kg/m3
10	200
12.5	195
20	186

Table 3.4: Recommended w/c for High Strength Concrete made with HRWRA as a function of maximum-size aggregates as shown in Table 8 of IS: 10262

Target Compressive Strength at 28 days, N/mm^2	Water cement ratio		
	Nominal Maximum Size of Aggregate, mm		
	10mm	12.5mm	20mm
70	0.36	0.35	0.33
75	0.34	0.33	0.31
80	0.32	0.31	0.29
85	0.30	0.29	0.27
90	0.28	0.27	0.26
100	0.26	0.25	0.24

Table 3.5: Recommended dosages of different pozzolanic materials for high strength mixes as in Table 9 of IS: 10262

Pozzolanic Material	Recommended dosages, percentage by mass of total cementitious materials
Fly ash	15-30
Ground Granulated Blast Furnace Slag	25-50
Silica Fume	5-10

Table 3.6: Coarse Aggregate Volume /Unit Volume of Total Aggregate (w/c=0.3)

Nominal Maximum Size of Aggregate(mm)	Coarse Aggregate Volume / Unit Volume of total Aggregate (for 3 diff. Zones of Fine Aggregates)		
	ZoneIII	ZoneII	ZoneI
10	0.56	0.54	0.52
12.5	0.58	0.56	0.54
20	0.68	0.66	0.64

CHAPTER 4
STATISTICAL METHODS

4.1 INTRODUCTION TO 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 also used periodically in obtaining the optimum concrete mixture design [8] and [20]. Statistical methods are advancement over fully experimental methods, in which, rather than selecting one starting mix proportion and then adjusting by trial and error for acquiring the optimum solution, a set of trial batches housing a chosen range of proportions for each mixture component is defined conforming the established statistical procedures. A certain amount of experimental work is also required by these methods. Trial batches are carried out; test specimens are fabricated and tested. Standard statistical methods are then used to analyze experimental results. These methods incorporate fitting empirical models to the data for each performance criterion. In these models, resultant concrete property (response) such as strength, slump, or cost is expressed as an algebraic function of factors such as w/c ratio, cement content, chemical admixture dosage, and percent pozzolana replacement. The influence of various factors in concrete mix proportioning has to be studied. After the characterization of the response by mathematical model, several analyses are possible. For example, a user can determine which mixture proportions will yield desired properties. A user also can optimize any property subject to constraints on other properties. Simultaneous optimization to meet more than one constraint is also possible. For example, one can resolve the lowest cost mixture with strength greater than a specified value, air content within a given range and also, slump within a given range. All this is possible in one optimization step. The basic approach is to cut down the number of trial mixes without compromising with the strength and slump of the mixture (the two main properties). Also, if possible economy is taken care of.

A statistical approach must be intervened not only to design the test but also to interpret the results obtained and define the mathematical models on not only empirical but also physical basis

4.2 APPROACH

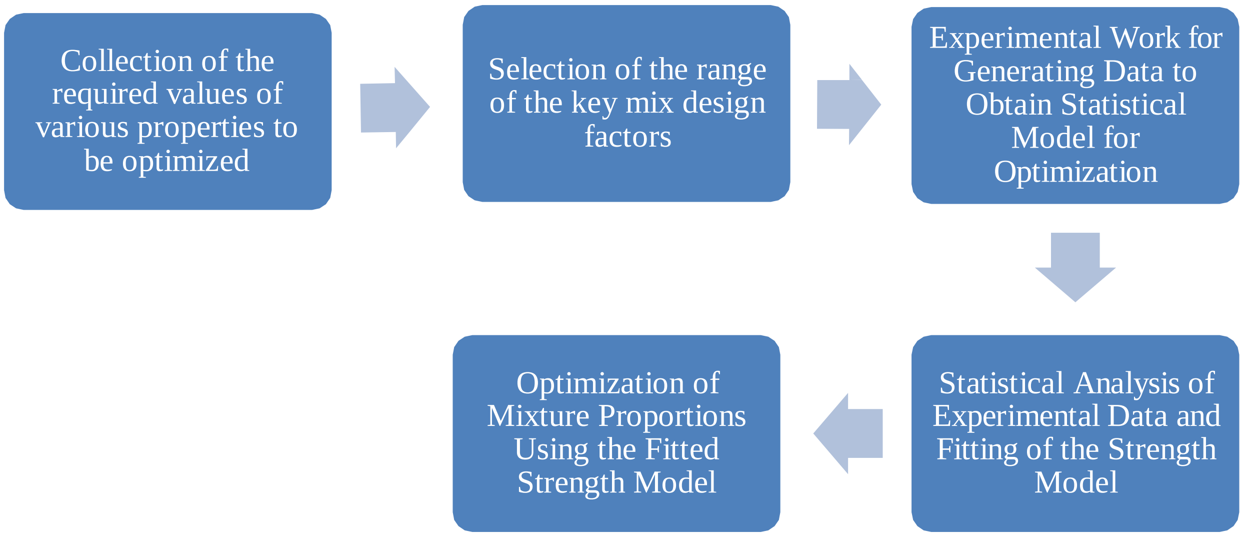


Figure 4.1: Basic approach of statistical method

The approach aims to reduce the number of trails by planning experimental works and static analysis of the data so generated. This analysis can be further used in future for the optimization of the concrete mix design.

It consists of about 4 steps:-

(a) Collection of the required values of various properties to be optimized: This step is the basic and the foremost step and involves the collection of the information regarding the required values of strength, slump and in addition to these two, exposure conditions (for durability requirements).the workability values depend on various factors such as the mode of transportation, handling, placing of the concrete etc. the strength is, on the other hand dependent upon the structural requirements for concrete protected from exposure to extreme conditions such as application of deicing chemicals or aggressive substances. ACI 318 has specified minimum design compressive strengths depending upon the exposure conditions. The durability requirements are satisfied that the cementitious materials are in a specified range i.e. not greater than or less than the given limits.

(b) Selection of the range of the key mix design factors: Selection of the range of the three key mixture design factors, namely, supplementary cementitious materials (SCM) content, water over binder ratio, and fine over total aggregate ratio, which mainly affect the quality of concrete will be made to ensure that ample experimental data are generated to retrieve a regression model for compressive strength which can be used to optimize the mixture proportions meeting the stated characteristic performance of concrete. For example if the water/cement ratio is selected too less than the water available would be low, which would demand higher doses of superplasticizer. Also the problem in transporting, handling and placing would be faced. The range should be so selected that we reach to the maximum level of packing of the aggregates.

(c) Experimental Work for Generating Data to Obtain Statistical Model for Optimization: An experimental work should be supervised involving designing, preparing, and testing various trial mixtures in accordance to the full factorial experiment design keeping in mind the various probable combinations of the levels of the mixture variables within the selected range of variation. The workability of each trial mixture should be equal to or more than the stated value. In case if superplasticizer is needed to reach the required workability, the cost of superplasticizer should be added to the cost of the cement. After finalizing the dosage of superplasticizer established on the intended workability for each of the trial mixtures, the cubical or cylindrical specimens are to be prepared, cured for 28 days, and then tested for compressive strength for developing data to attain statistical model for strength to be used for optimization.

(d) Statistical Analysis of Experimental Data and Fitting of the Strength Model: MS Excel and SPSS can be used to perform the data entry and analysis and create tables and graphs. They both can handle a large amount of data effectively. They basically examine the sense of the factors considered for developing the strength and slump model and subsequently fitting an empirical model for both in terms of the significant mixture factors using polynomial regression. In the study of variance, the statistical terminologies are used. They are as follows:-

Degree of Freedom (DF): Degree of freedom is the number of values in the final calculation of a statistic that are free to vary. DF = $n - 1$, where n represents the number of groups.

Error (Residual): It is the amount by which an observed variate differs from the value predicted by the assumed statistical model.

Sum of Squares (SS): It is defined as the square of distance between each data point (X_i) and the sample mean (X), summed for all n data points.

$$SS=\sum_{i-1}^{n}(X_i\text{-}X)^2$$

where, X_i represents the ith observation and X represents the sample mean.

Mean Square (MS): It is the sum of squares divided by the degrees of freedom.

F-Ratio: It is ratio of MS of the concerned factor to the MS of the error. A higher F-ratio indicates a significant effect of the factor.

P-Value: It is the measure of acceptance of a factor based on a standard that not more than 5% (0.05 levels) of the difference is due to chance or sampling error. In other words, if the P value for a factor is 0.05 or more, it is accepted [21].

(e) <u>Optimization of Mixture Proportions Using the Fitted Strength Model:</u> The statistical model for the compressive strength and slump [22] derived utilizing the experimental model can be used to obtain the optimal mixture proportions satisfying the specified characteristic performance of concrete as required constraints. The mixture satisfying all the constraints and having the lowest requirements of cement and superplasticizer would be considered as optimum mixture.

After this, experiment has to be conducted. For this, trial mixtures are prepared with varying quantities of the key factors mentioned above. The specific gravity, sieve analysis and water absorption of the aggregates should be listed along with the specific gravities of water and other cementitious materials. Compressive strength and slump tests are performed and then these values are compared with those obtained from the statistical analysis.

The statistical models improve the predictive performance; however, there is a danger in adding more and more terms to the model. The problem is that the extra terms included might only be creating random noise in the data and not actually improving the performance.

Here, the correlation comes into picture. There is a provision in MATLAB which provides correlation and the correlation is expressed in the form of numerical digits. Only relations having correlation greater than a specified lower limit are included in the mathematical model (equation). The correlation has the range of values from -1 and +1. The negative sign mean that with the increase in the value of one variable, the other decreases whereas the positive sign means that the increase in one causes the increase in the other. One can choose any level but then again too many chosen variable cause error and no accuracy.

In the present work various trials were carried out and then a final equation of strength and slump was finalized.

4.3 REGRESSION ANALYSIS

Regression analysis is a modeling technique which helps in studying the relation between a dependent (target) and independent variable (s) (predictor). This technique is used for time series modeling, forecasting, and finding the causal effect relationship between the two or more variables; e.g. - relationship between dosage of superplasticizer and subsequent effect on the slump can be studied with the assistance of regression.

It is an imperative tool that provides us with an aid of modeling and analyzing data. We can fit a curve / line to the data points in such a way that the differences between the distances of data points from the curve or line are minimized. It estimates the relationship between two or more variables. For example:

We want to estimate growth in compressive strength of concrete based on the replacement of cement with SCM. We also have a recent literature related to the same for quite an amount of mixes. With the help of this approach, we can predict the compressive strengths based on current & past information.

By the means of regression analysis, multiple benefits can be achieved which are as follows:

i. It can point out the significant relationships between dependent and independent variable.
ii. It can also specify the strength of impact of multiple independent variables on one dependent variable.

Regression analysis also permits us to evaluate the effect of variables appraised on different scales, such as the effect of w/c ratio on the workability of concrete. These benefits help researchers to eradicate and propose the best set of variables that can be employed for building predictive models.

CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 EXPERIMENTAL PROGRAM

This section describes in detail the experimental procedure followed for the measurement of compressive strength and workability of the concrete mixes made with 5% of silica fume and 15% fly ash as partial replacement of cement.

5.1.1 Materials and its Properties

Materials used in the study are water, OPC-43, Coarse Aggregates, Fine Aggregates, Silica Fume, Fly Ash and Superplasticizer (Auromix 400). Detailed characteristics are given in below sections.

5.1.1.1 Cement- Ordinary Portland Cement (OPC) – 43

In our study OPC of 43 grade was used. The physical and chemical properties of OPC 43 were tested in accordance with Indian Standard specifications (IS-1489 part 1:1991) and are listed in table 5.1 and table 5.2 respectively.

Table 5.1: Physical properties of OPC-43

Physical Properties	**Observations**	**Standard Values**
Standard Consistency (%)	23	-
Initial Setting Time (minutes)	123	Not less than 30 minutes
Final Setting Time (minutes)	270	Not more than 600 minutes
Specific Gravity	3.068	-

Table 5.2: Chemical Properties of OPC-43

Constituent	**Amount (%)**
SiO_2	21.25

Al_2O_3	4.74
Fe_2O_3	4.30
CaO	63.49
MgO	1.02
K_2O	0.78
Na_2O	0.30
SO_3	2.93
TiO_2	0.36

5.1.1.2 Coarse Aggregates

Crushed stone with maximum size of aggregate 10mm (nominal size) was employed as coarse aggregate for all the 21 mixes. For the removal of dirt and dust, the aggregates were washed and dried to surface dry condition. Measurement of its physical properties and sieve size analysis was done in accordance with the Indian Standard specifications (Table 4, IS: 383-1970) and are listed in table 5.3 and table 5.4 respectively.

Table 5.3: Physical properties of coarse aggregates

Properties	**Observations**
Colour	Grey
Specific gravity	2.80
Maximum size	10mm
Shape	Angular

Table 5.4: Sieve size analysis of coarse aggregates

S.No.	**IS Sieve (mm)**	**Weight Retained (gm)**	**%age Retained**	**%age Passing**	**Cumulative % retained**
1	80	0.00	0.00	100.00	0.00

2	40	0.00	0.00	100.00	0.00
3	20	3650	36.5	63.5	36.5
4	10	5190	51.9	11.6	88.4
5	4.75	1160	11.6	0.00	100
6	2.36	0	0.00	0.00	100
7	1.18	0	0.00	0.00	100
8	600 µ	0	0.00	0.00	100
9	300 µ	0	0.00	0.00	100
10	150 µ	0	0.00	0.00	100
11	Pan	0	0.00	**Sum**	**724.9**
Total		**10000**		**FM = 7.24**	

5.1.1.3 Fine Aggregates

Natural sand with maximum size of aggregates 4.75mm were utilized as fine aggregates. According to the IS 383 fine aggregate are divided into four grading zones i.e. Grade I to IV. These zones become eventually finer from grading zone I to IV. For this study, fine aggregates were conforming to grading zone II and were supplied by a local supplier in Patiala. The fine aggregates were washed to eradicate contaminates like silt and clay and then dried to get rid of the excess water. Measurement of its physical properties and sieve size analysis was done in accordance with the Indian Standard specifications (IS: 383-1970) and are listed in table 5.5 and table 5.6 respectively.

. Table 5.5: Physical properties of fine aggregates

Properties	**Observed values**
Type	Natural Sand
Specific gravity	2.65
Grading Zone	II
Fineness modulus	3.02

Table 5.6: Sieve analysis of fine aggregates

S.No.	IS Sieve (mm)	Weight Retained (gm)	%age Retained	%age Passing	Cumulative % retained
1	4.75	31	3.1	96.9	3.1
2	2.36	137	13.7	83.2	16.8
3	1.18	238	23.8	59.4	40.6
4	600 µ	168	16.8	42.6	57.4
5	300 µ	316	31.6	11	89
6	150 µ	65	6.5	4.5	95.5
7	Pan	45	4.5	0	
Total		**1000**		**Sum**	**302.4**
Zone II			**FM = 3.02**		

5.1.1.4 Supplementary Cementitious Materials (SCM)

(i) Fly Ash: It is capable of producing HPC which can result in lesser water demand and reduced cost. However, the early strength gain may be reduced when fly ash is added [23]. The fly ash used in this study was obtained from Deenbandhu Chhotu Ram Thermal Power Station, Yamuna Nagar, Haryana, India.

Figure 5.1: Oven dried Fly Ash

(ii) Silica Fume: A study [24] has shown that the pozzolanic activity of silica fume lowers due to its alkali content. It also states that the flowability of fresh concrete increases with the decrease in the carbon content, therefore, white SF is chosen. The silica fume was obtained from a ceramics factory named Haryana Ceramics located in Ambala City, Haryana. Its picture and EDS results are shown below.

Figure 5.2: Silica Fume used in the experimental work

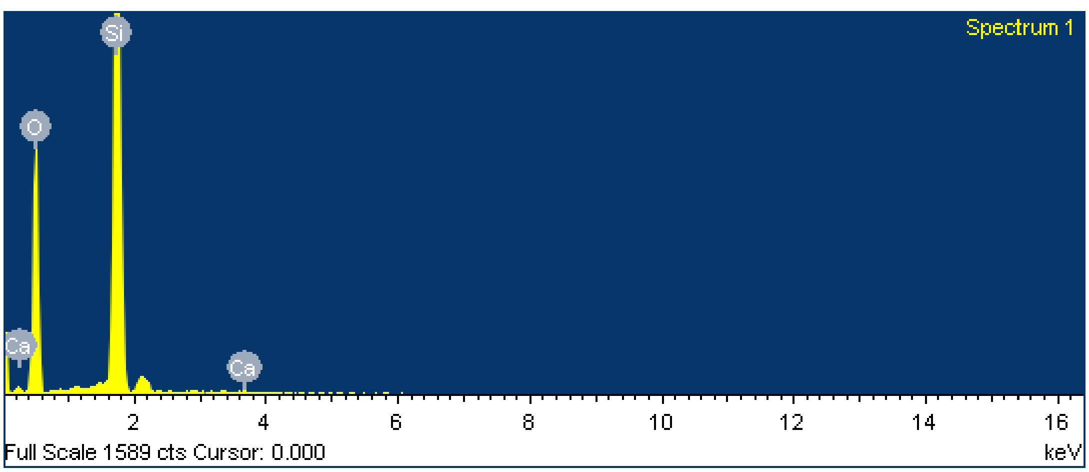


Figure 5.3: Energy-dispersive X-ray spectrum of silica fume sample [Sophisticated Analytical Instruments Laboratories (SAI Labs), Patiala]

Table 5.7: Elements analyzed in EDS of silica fume

Element	Weight %	Atomic %
O K	51.80	65.36
Si K	48.16	34.62
Ca K	0.04	0.02

5.1.1.5 Superplasticizer- Auramix 400

Auramix 400 is a high performance superplasticizer, based on a polycarboxylic ether polymer with long lateral chains, intended for applications where high water reduction and long workability retention are required, and it has been developed for use in self-compacting concrete, high performance concrete, pumped concrete, concrete requiring long workability retention. It complies with IS: 9103-1999 [25].

Its various advantages are:-

- Low viscosity suitable for pumping of different grades of concrete to higher floors
- Higher modulous of elasticity
- Improved adhesion to reinforcing and pre-stressing steel
- Better resistance to carbonation
- Lower permeability
- Better resistance to aggressive atmospheric conditions
- Reduced shrinkage and creep
- Increased durability

Figure 5.4: Auromix 400

Table 5.8: Properties of Auromix 400 [26]

Properties	Observed Values
Facade	Light yellow coloured viscous liquid
pH	6.3
Volumetric mass (at 20^0 C)	1090 kg/m^3
Chloride content	-
Alkali content	Typically less than 1.5 gm Na_2O equivalent / liter of admixture.

5.1.2 Concrete Specimens

In the starting, 21 mix compositions (3 sets of 7 mixes complying to 50, 80 and 120mm slump) were developed according to the IS 10262 and trials were done so as to verify them. Adjustments to the initial compositions were made and finally, 84 cube specimens (4 replicas of each mix) of size 100x100x100 mm were casted. All the concrete mixes were prepared in hand feed round concrete mixer which can mix upto 10 cubic feet of dry mix at one time. The sequence of batching consisted of dry mixing the ingredients for one minute then adding the water with the superplasticizer slowly and again mixing for about 4 to 6 minutes until a homogenous paste is prepared. Slump test was carried on the fresh concrete by slump cone and tamping rod and the results were recorded. Placing the fresh concrete in the cubes and compaction was done on the table vibration. The specimens were left untouched and were demolded in 28-30hours. They were kept at normal room temperature, in normal tap water for curing for 28 days.

Figure 5.5: Round concrete mixer with dry ingredients

Figure 5.6: Compaction of concrete on Table Vibrator

5.1.3 Test Results

As mentioned above, the slump test was performed on the freshly prepared concrete within two minutes of preparation for showing the flow range of the concrete. U- Box and V-Box are some other methods to measure but slump is more reliable. Further, to obtain the compressive strength of the concrete, 4 cubes of each mix composition were casted and tested after 28 days. They were tested under the ACTM (Automatic Compression Testing Machine) and the results are given below.

Figure 5.7: Slump test apparatus- slump cone and tamping rod

Figure 5.8: Cube testing after 28 days under ACTM

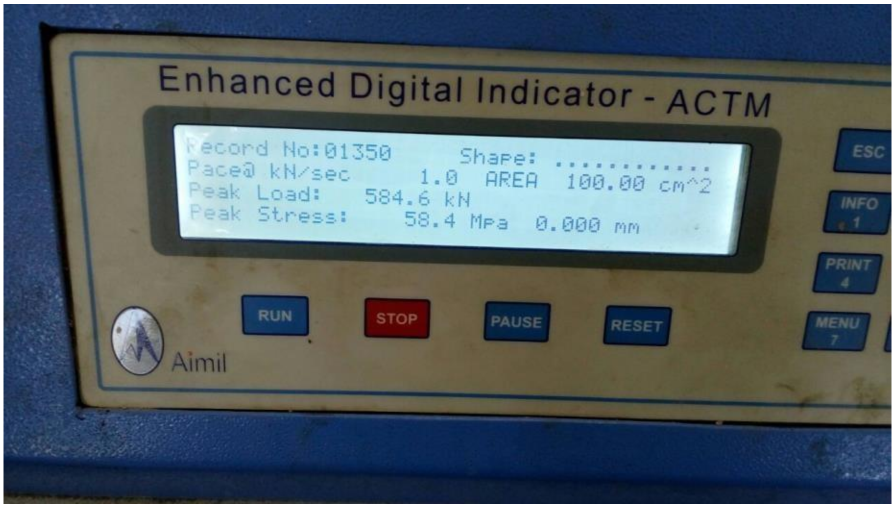


Figure 5.9: ACTM showing compressive test result

5.1.4 Mix Design

The below mentioned are the values of the various constituents in kg/m^3. These values were then multiplied by the volume of 100mm cube for final casting.

Table 5.9: Trial concrete mix design of 21 mixes

Water=140kg ; Required Slump=50mm						
Mix	**Cement**	**Fine Aggregate**	**Coarse Aggregate**	**Silica Fume**	**Fly Ash**	**SP**
M60	343.213	840.335	995.16	21.39	64.197	5.25
M65	362.353	828.438	965.01	22.647	67.94	8.5
M70	385	818.435	957.4	24.062	72.187	11.5
M75	410.76	807.23	951.286	25.67	76.9	6
M80	440.3	783.78	939.74	27.5	82.5	9
M85	465.302	772.182	933.08	28.518	85.55	12.5
M90	473.85	759.89	925.421	29.61	88.85	6.75
Water=145.04kg ; Required Slump=80mm10						
M60	354.55	855.71	979.72	22.16	66.47	10
M65	375.398	815.56	950.79	23.462	70.38	13.75
M70	398.85	805.85	941.96	24.93	74.785	7.5

M75	425.453	793.512	936.116	26.59	79.77	11.25
M80	455.85	769.78	922.95	28.49	85.77	15.25
M85	472.73	757.824	915.731	29.54	88.635	8.5
M90	490.905	745.27	902.618	30.68	92.045	12.5
Water=151.76kg ; Required Slump=120mm						
M60	370.9	838.68	960.794	23.185	69.55	17
M65	392.78	798.74	931.86	24.55	73.647	9.25
M70	417.34	789.12	921.4	26.083	78.25	13.25
M75	445.165	775.235	913.59	27.82	83.468	17.75
M80	476.96	750.96	900.38	29.81	89.43	10
M85	494.63	738.68	892.6	30.91	92.742	14.25
M90	513.65	725.77	883.88	32.103	96.309	19

5.2 RESULTS OF EXPERIMENTS PERFORMED IN LABORATORY

w = water

b = binder i.e. cement, fly ash and silica fume

w_b = water over binder ratio

f_t = fine aggregates over total aggregates ratio

sp = superplasticizer

sf_b = silica fume over binder ratio

fly_b = fly ash over binder ratio

sp_b = superplasticizer over binder ratio

QcXf_t = cementitious materials multiplied by fine aggregates over total aggregates ratio

w_bxf_t = water over binder ratio multiplied by fine aggregates over total aggregates ratio

bxw_b = water into water over binder ratio

Table 5.10: Experimental results and analysis

MIX	**Strength achieved**	**Slump achieved**	**water**	**w_b**	**f_t**	**sp**	**sf_b**	**fly_b**	**sp_b**	**QcXf_t**	**w_bxf_t**	**bxw_b**
M60(50mm)	60	45	0.86	0.327	0.4736	0.021	0.049	0.149	0.0078	1.27	0.154867	0.86
M60(50mm)	56.3	45	0.86	0.327	0.4736	0.021	0.049	0.149	0.0078	1.27	0.154867	0.86

M60(50mm)	60.7	45	0.86	0.327	0.4736	0.021	0.049	0.149	0.0078	1.27	0.154867	0.86
M60(50mm)	53.4	45	0.86	0.327	0.4736	0.021	0.049	0.149	0.0078	1.27	0.154867	0.86
M60(80mm)	57.7	90	0.89	0.327	0.514	0.034	0.049	0.149	0.012	1.429	0.168078	0.89
M60(80mm)	48.4	90	0.89	0.327	0.514	0.034	0.049	0.149	0.012	1.429	0.168078	0.89
M60(80mm)	62.1	90	0.89	0.327	0.514	0.034	0.049	0.149	0.012	1.429	0.168078	0.89
M60(80mm)	55	90	0.89	0.327	0.514	0.034	0.049	0.149	0.012	1.429	0.168078	0.89
M60(120mm)	48.9	150	0.931	0.327	0.4508	0.046	0.049	0.149	0.015	1.312	0.147412	0.931
M60(120mm)	56.2	150	0.931	0.327	0.4508	0.046	0.049	0.149	0.015	1.312	0.147412	0.931
M60(120mm)	52.6	150	0.931	0.327	0.4508	0.046	0.049	0.149	0.015	1.312	0.147412	0.931
M60(120mm)	61	150	0.931	0.327	0.4508	0.046	0.049	0.149	0.015	1.312	0.147412	0.931
M65(50mm)	57	35	0.877	0.308	0.4674	0.024	0.049	0.149	0.0084	1.329	0.143959	0.877
M65(50mm)	49.6	35	0.877	0.308	0.4674	0.024	0.049	0.149	0.0084	1.329	0.143959	0.877
M65(50mm)	54.2	35	0.877	0.308	0.4674	0.024	0.049	0.149	0.0084	1.329	0.143959	0.877
M65(50mm)	53	35	0.877	0.308	0.4674	0.024	0.049	0.149	0.0084	1.329	0.143959	0.877
M65(80mm)	58.3	85	0.911	0.308	0.4616	0.036	0.049	0.149	0.0122	1.361	0.142173	0.911
M65(80mm)	53.8	85	0.911	0.308	0.4616	0.036	0.049	0.149	0.0122	1.361	0.142173	0.911
M65(80mm)	64	85	0.911	0.308	0.4616	0.036	0.049	0.149	0.0122	1.361	0.142173	0.911
M65(80mm)	65.2	85	0.911	0.308	0.4616	0.036	0.049	0.149	0.0122	1.361	0.142173	0.911
M65(120mm)	62.9	125	0.953	0.308	0.4734	0.05	0.049	0.149	0.0162	1.461	0.145807	0.953
M65(120mm)	57.7	125	0.953	0.308	0.4734	0.05	0.049	0.149	0.0162	1.461	0.145807	0.953
M65(120mm)	54	125	0.953	0.308	0.4734	0.05	0.049	0.149	0.0162	1.461	0.145807	0.953
M65(120mm)	54	125	0.953	0.308	0.4734	0.05	0.049	0.149	0.0162	1.461	0.145807	0.953
M70(50mm)	68.3	52	0.877	0.29	0.4638	0.027	0.049	0.149	0.0089	1.401	0.134502	0.877
M70(50mm)	70.1	52	0.877	0.29	0.4638	0.027	0.049	0.149	0.0089	1.401	0.134502	0.877
M70(50mm)	68	52	0.877	0.29	0.4638	0.027	0.049	0.149	0.0089	1.401	0.134502	0.877
M70(50mm)	59.3	52	0.877	0.29	0.4638	0.027	0.049	0.149	0.0089	1.401	0.134502	0.877
M70(80mm)	70	80	0.906	0.29	0.4612	0.04	0.049	0.149	0.0128	1.442	0.133748	0.906
M70(80mm)	61	80	0.906	0.29	0.4612	0.04	0.049	0.149	0.0128	1.442	0.133748	0.906
M70(80mm)	63.7	80	0.906	0.29	0.4612	0.04	0.049	0.149	0.0128	1.442	0.133748	0.906
M70(80mm)	62	80	0.906	0.29	0.4612	0.04	0.049	0.149	0.0128	1.442	0.133748	0.906
M70(120mm)	67.4	130	0.950	0.29	0.4643	0.055	0.049	0.149	0.0168	1.5201	0.134647	0.950
M70(120mm)	71.1	130	0.950	0.29	0.4643	0.055	0.049	0.149	0.0168	1.5201	0.134647	0.950
M70(120mm)	58.5	130	0.950	0.29	0.4643	0.055	0.049	0.149	0.0168	1.5201	0.134647	0.950
M70(120mm)	63.0	130	0.950	0.29	0.4643	0.055	0.049	0.149	0.0168	1.5201	0.134647	0.950
M75(50mm)	67.6	40	0.877	0.272	0.4592	0.03	0.049	0.149	0.0093	1.4804	0.124902	0.877
M75(50mm)	72.4	40	0.877	0.272	0.4592	0.03	0.049	0.149	0.0093	1.4804	0.124902	0.877

M75(50mm)	64.0	40	0.877	0.272	0.4592	0.03	0.049	0.149	0.0093	1.4804	0.124902	0.877
M75(50mm)	70.0	40	0.877	0.272	0.4592	0.03	0.049	0.149	0.0093	1.4804	0.124902	0.877
M75(80mm)	74.4	85	0.907	0.272	0.4589	0.045	0.049	0.149	0.0135	1.532	0.124821	0.907
M75(80mm)	73.1	85	0.907	0.272	0.4589	0.045	0.049	0.149	0.0135	1.532	0.124821	0.907
M75(80mm)	74.4	85	0.907	0.272	0.4589	0.045	0.049	0.149	0.0135	1.532	0.124821	0.907
M75(80mm)	58.6	85	0.907	0.272	0.4589	0.045	0.049	0.149	0.0135	1.532	0.124821	0.907
M75(120mm)	72.6	130	0.948	0.272	0.4603	0.061	0.049	0.149	0.0175	1.605	0.125202	0.948
M75(120mm)	71.9	130	0.948	0.272	0.4603	0.061	0.049	0.149	0.0175	1.605	0.125202	0.948
M75(120mm)	59.1	130	0.948	0.272	0.4603	0.061	0.049	0.149	0.0175	1.605	0.125202	0.948
M75(120mm)	64.3	130	0.948	0.272	0.4603	0.061	0.049	0.149	0.0175	1.605	0.125202	0.948
M80(50mm)	69.6	55	0.876	0.254	0.4547	0.034	0.049	0.149	0.0098	1.569	0.115494	0.876
M80(50mm)	79.4	55	0.876	0.254	0.4547	0.034	0.049	0.149	0.0098	1.569	0.115494	0.876
M80(50mm)	73.1	55	0.876	0.254	0.4547	0.034	0.049	0.149	0.0098	1.569	0.115494	0.876
M80(50mm)	81.0	55	0.876	0.254	0.4547	0.034	0.049	0.149	0.0098	1.569	0.115494	0.876
M80(80mm)	74.3	90	0.908	0.254	0.4548	0.05	0.049	0.149	0.014	1.626	0.115519	0.908
M80(80mm)	69.1	90	0.908	0.254	0.4548	0.05	0.049	0.149	0.014	1.626	0.115519	0.908
M80(80mm)	80.6	90	0.908	0.254	0.4548	0.05	0.049	0.149	0.014	1.626	0.115519	0.908
M80(80mm)	72.0	90	0.908	0.254	0.4548	0.05	0.049	0.149	0.014	1.626	0.115519	0.908
M80(120mm)	78.1	130	0.948	0.254	0.4551	0.068	0.049	0.149	0.0176	1.724	0.115595	0.948
M80(120mm)	76.3	130	0.948	0.254	0.4551	0.068	0.049	0.149	0.0176	1.724	0.115595	0.948
M80(120mm)	77.0	130	0.948	0.254	0.4551	0.068	0.049	0.149	0.0176	1.724	0.115595	0.948
M80(120mm)	67.3	130	0.948	0.254	0.4551	0.068	0.049	0.149	0.0176	1.724	0.115595	0.948
M85(50mm)	84.6	55	0.876	0.245	0.4487	0.037	0.049	0.149	0.0103	1.604	0.109932	0.876
M85(50mm)	73.4	55	0.876	0.245	0.4487	0.037	0.049	0.149	0.0103	1.604	0.109932	0.876
M85(50mm)	78.2	55	0.876	0.245	0.4487	0.037	0.049	0.149	0.0103	1.604	0.109932	0.876
M85(50mm)	72.0	55	0.876	0.245	0.4487	0.037	0.049	0.149	0.0103	1.604	0.109932	0.876
M85(80mm)	79.2	92	0.905	0.245	0.4529	0.053	0.049	0.149	0.0143	1.672	0.110961	0.905
M85(80mm)	76.0	92	0.905	0.245	0.4529	0.053	0.049	0.149	0.0143	1.672	0.110961	0.905
M85(80mm)	80.4	92	0.905	0.245	0.4529	0.053	0.049	0.149	0.0143	1.672	0.110961	0.905
M85(80mm)	77.1	92	0.905	0.245	0.4529	0.053	0.049	0.149	0.0143	1.672	0.110961	0.905
M85(120mm)	84.3	120	0.952	0.245	0.4531	0.071	0.049	0.149	0.0183	1.761	0.11101	0.952
M85(120mm)	88.1	120	0.952	0.245	0.4531	0.071	0.049	0.149	0.0183	1.761	0.11101	0.952
M85(120mm)	74.2	120	0.952	0.245	0.4531	0.071	0.049	0.149	0.0183	1.761	0.11101	0.952
M85(120mm)	81.0	120	0.952	0.245	0.4531	0.071	0.049	0.149	0.0183	1.761	0.11101	0.952
M90(50mm)	81.5	55	0.876	0.236	0.434	0.04	0.049	0.149	0.0108	1.6114	0.102613	0.876
M90(50mm)	83.2	55	0.876	0.236	0.434	0.04	0.049	0.149	0.0108	1.6114	0.102613	0.876

M90(50mm)	80.4	55	0.876	0.236	0.434	0.04	0.049	0.149	0.0108	1.6114	0.102613	0.876
M90(50mm)	87.0	55	0.876	0.236	0.434	0.04	0.049	0.149	0.0108	1.6114	0.102613	0.876
M90(80mm)	80.9	95	0.908	0.236	0.4521	0.057	0.049	0.149	0.0148	1.7406	0.106696	0.908
M90(80mm)	86.3	95	0.908	0.236	0.4521	0.057	0.049	0.149	0.0148	1.7406	0.106696	0.908
M90(80mm)	77.2	95	0.908	0.236	0.4521	0.057	0.049	0.149	0.0148	1.7406	0.106696	0.908
M90(80mm)	84.0	95	0.908	0.236	0.4521	0.057	0.049	0.149	0.0148	1.7406	0.106696	0.908
M90(120mm)	81.3	120	0.950	0.236	0.451	0.076	0.049	0.149	0.0189	1.806	0.106436	0.950
M90(120mm)	78.0	120	0.950	0.236	0.451	0.076	0.049	0.149	0.0189	1.806	0.106436	0.950
M90(120mm)	82.0	120	0.950	0.236	0.451	0.076	0.049	0.149	0.0189	1.806	0.106436	0.950
M90(120mm)	80.8	120	0.950	0.236	0.451	0.076	0.049	0.149	0.0189	1.806	0.106436	0.950

5.3 EFFECT OF SUPERPLASTICIZER ON SLUMP

The fig. 5.10 displays that for a fixed amount of water, the superplasticizer dosage increases if the slump requirement increases. Also, for higher slump values, higher dosage of superplasticizer is necessary to maintain the concrete flow.

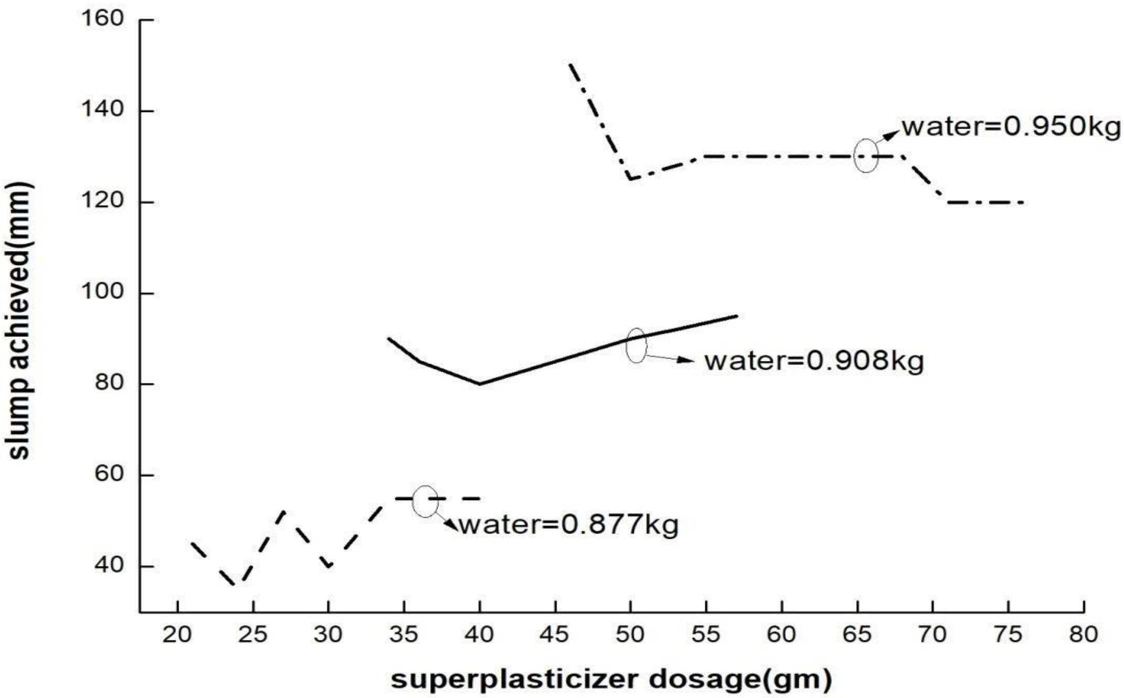


Figure 5.10: Superplasticizer dosage v/s slump achieved in laboratory

5.4 EFFECT OF WATER BINDER RATIO ON STRENGTH

From the fig. 5.11, the relation between the slump and w/b ratio is indirect i.e. when strength increases, the w/b ratio decreases. This may be because for a particular slump, the water quantity is fixed, so, when the w/b ratio increases, it leads the decrease in the binder content. Lesser surface area of the aggregates is covered by this content of binder, therefore, the strength decreases with the increase in w/b ratio.

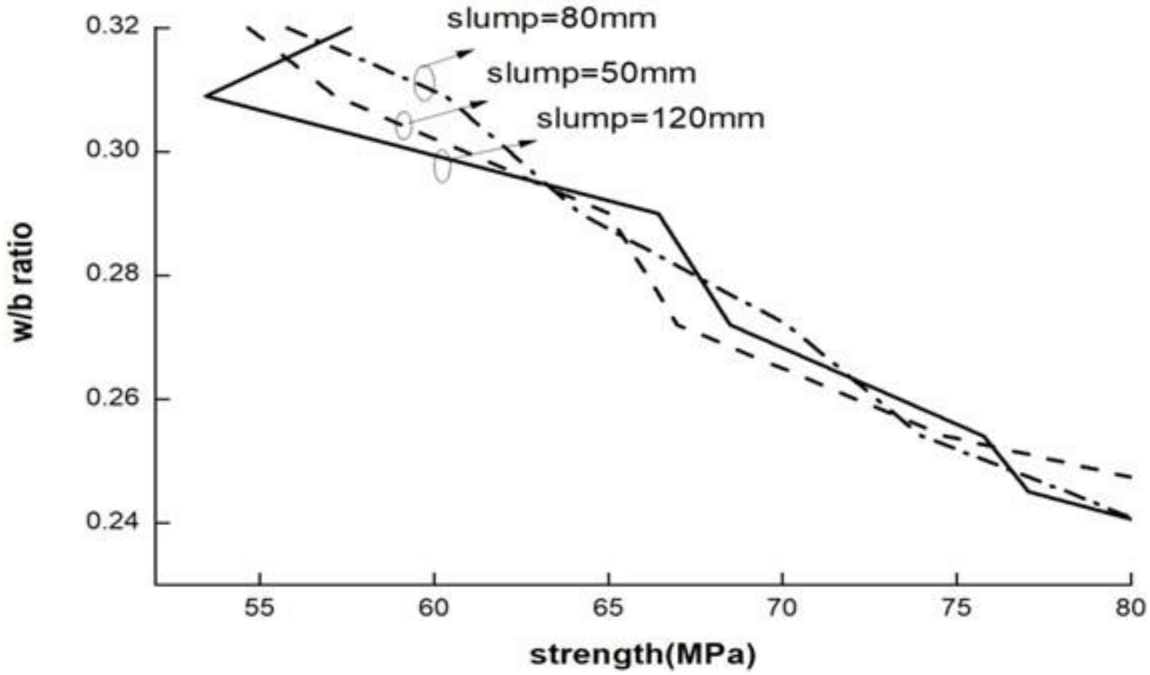


Figure 5.11: Compressive strength v/s water binder ratio

5.5 EFFECT ON SILICA FUME ON STRENGTH

From the fig. 5.12, it can be concluded that as the strength requirement increases in the concrete, the silica fume content has to be increased. Silica fume is a cementitious material and is used as a replacement of cement. So, as the strength requirement increases, the pozzolana requirement also increases. Further, if a compressive strength say 65MPa is fixed in the graph shown below, it can be observed that with the increasing amount of silica fume, the water requirement has decreased. This can be explained from the fact that the particles of silica fume are extremely fine (even finer than cement) and spherical, due to which they cause the concrete to flow by themselves, thus, decreasing the water requirement. Also, the superplastizer plays a vital role here.

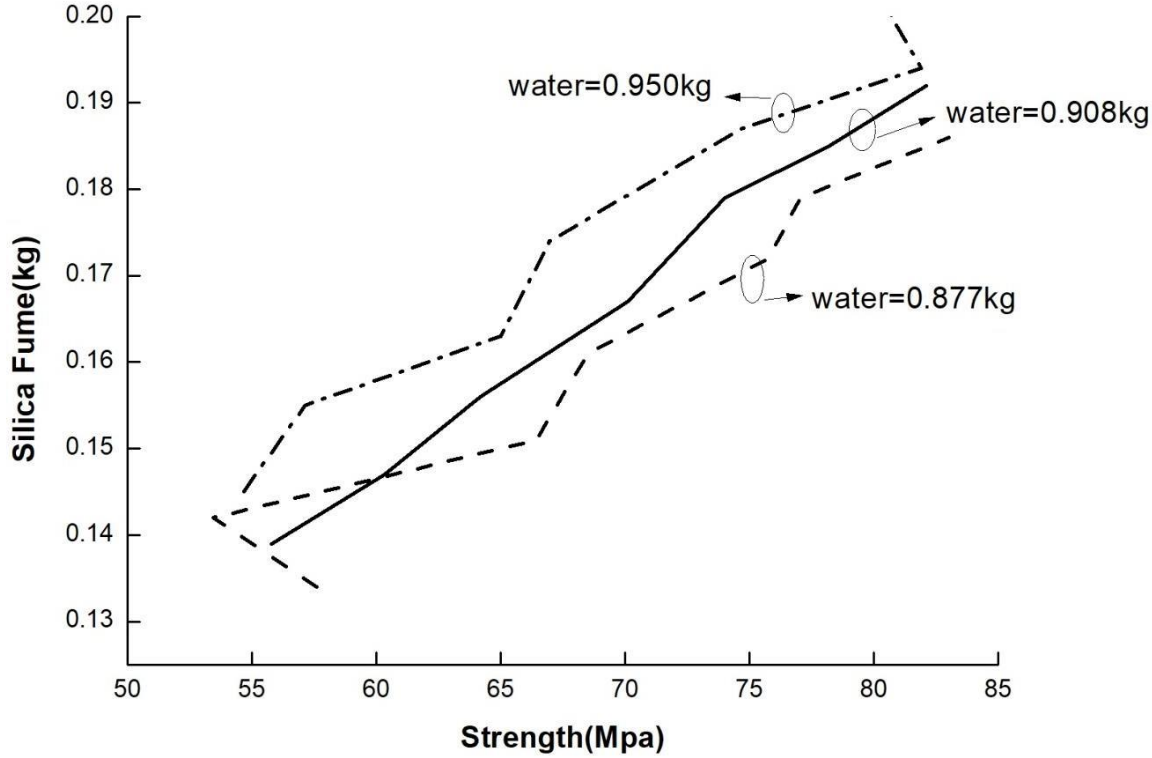


Figure 5.12: Compressive strength v/s silica fume amount

5.6 EFFECT OF FINE/TOTAL AGGREGATES ON STRENGTH

The fig. 5.13 demonstrates that with the increasing strength, the fine/total aggregates ratio decreases and becomes somewhat constant after some time. This may have the explanation that, the increase in the fine/total aggregates ratio means the decrease in the total aggregate content, which means that more binder is now available. This increased availability of binder increases the compressive strength of the concrete. This can also be understood in a way that the increase in the fine/total aggregates' ratio, fine aggregates content increases, better filling of the voids, hence, increased strength.

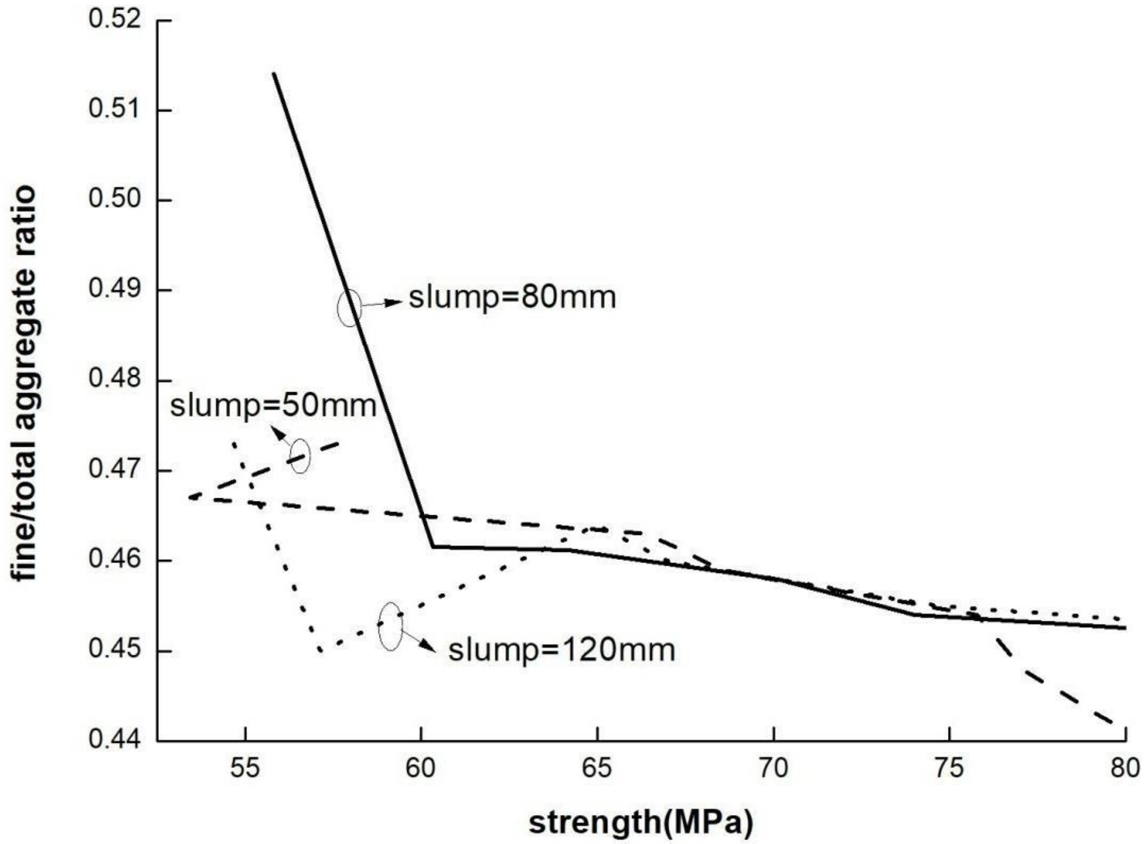


Figure 5.13: Compressive strength v/s fine aggregates over total aggregates ratio

5.7 EFFECT OF COARSE/TOTAL AGGREGATES ON STRENGTH

Fig. 5.14 exhibits that the increase in the coarse aggregate content leads to the decrease in the compressive strength. Also, higher slump is observed when the coarse aggregate content is lower. This may be explained, when the coarse aggregate content increases, voids in increase which disturbs the packing density of the concrete leading to the decrease in the compressive strength.

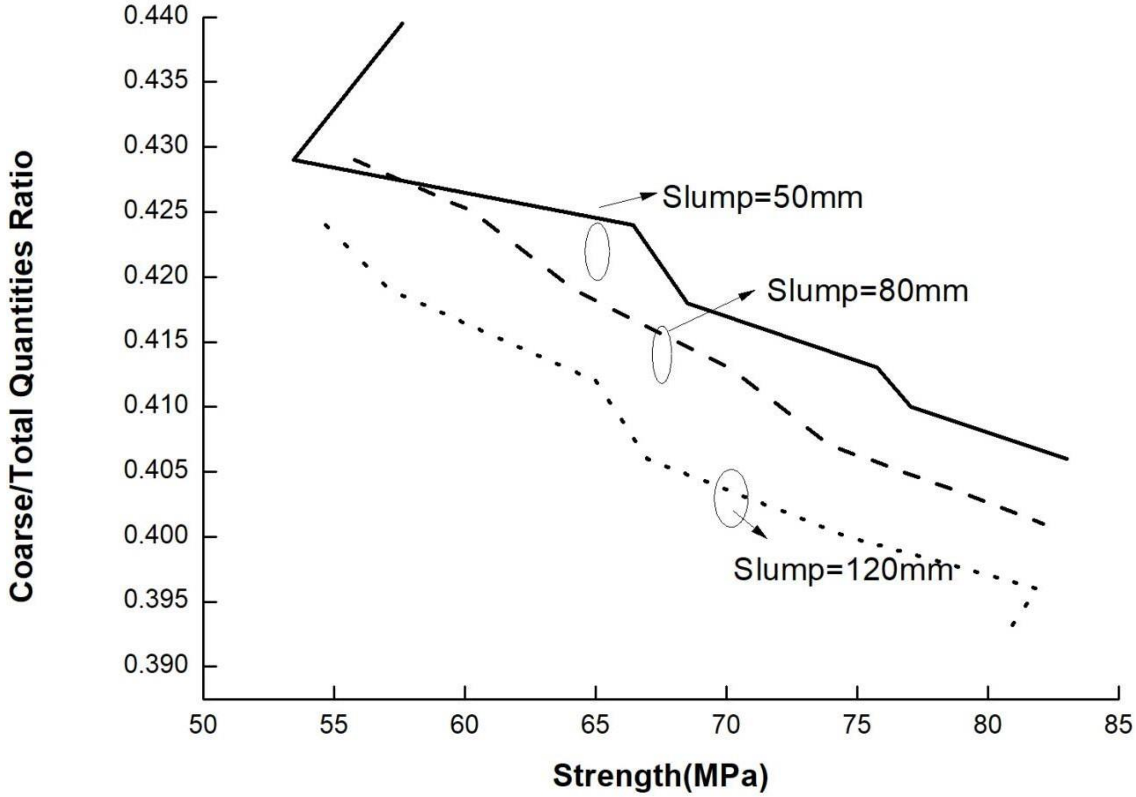


Figure 5.14: Compressive strength v/ coarse aggregates/total quantities' ratio

5.8 DEVELOPMENT OF MATHEMATICAL MODEL FOR STRENGTH AND SLUMP

The main objective of our study is to study the influence of various factors in concrete mix proportioning, to develop statistical model from experimental data and to optimize the mix the proportioning for available material and conditions. The cubes that were casted (explained in above sections) had different water to cement ratios, coarse aggregate over total aggregate ratio, silica fume content and their thorough compressive strengths and slump were measured. After this, correlation was applied on the data and different levels of correlation were set in order to obtain satisfying equations for strength and slump. Correlation helps us to decide which factors are to be chosen for the development of the mathematical model and which not. The positive values of correlation mean that the relation between two factors is positive i.e. they are proportional. Regression was then carried out and following two equations were developed.

Table 5.11: Factors used in mathematical model of strength and slump

Abbreviation	**Quantities (kg)**
a	Binder
a1	Cement
b	fine aggregates
c	coarse aggregates
d	water
e	fly ash
f	silica fume
g	superplasticizer
h	water

Strength = (116.5960) + 0.1449(a) + 0.0088(b) - 0.0281(c) - 0.7225(d) equation (5.1)

Slump = (-2137) – 7.1398(a1) + 28.624(e) + 37.6649(f) – 4.9499(g) + 0.2999(b) + 0.3520(c) + 10.0636(h) equation (5.2)

5.9 COMPARISON BETWEEN ANALYTICAL AND EXPERIMENTAL VALUES

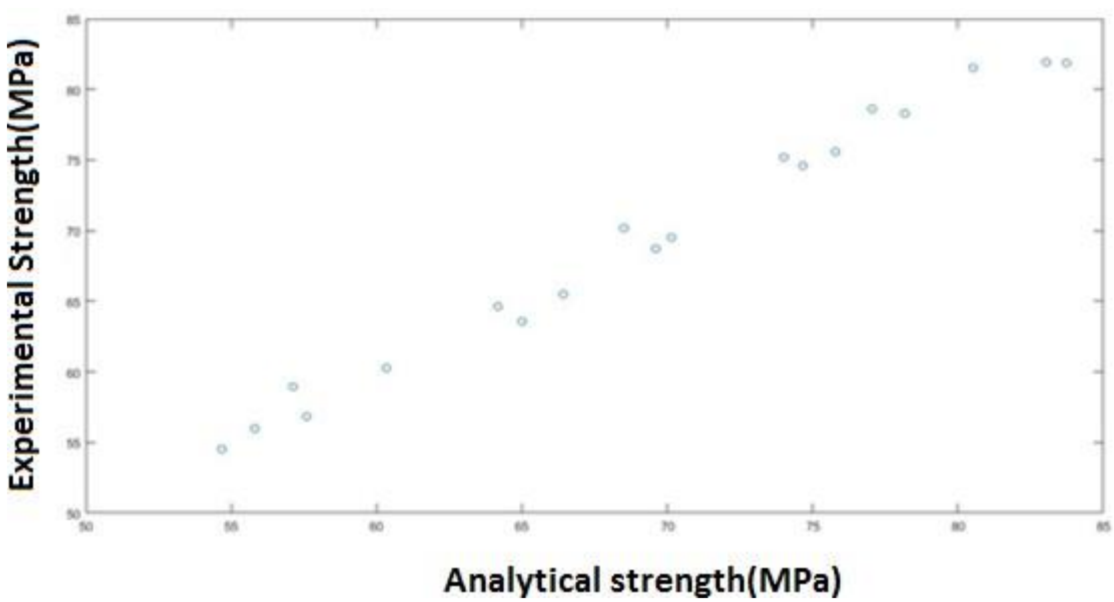


Figure 5.15: Analytical values of strength v/s experimental values of strength

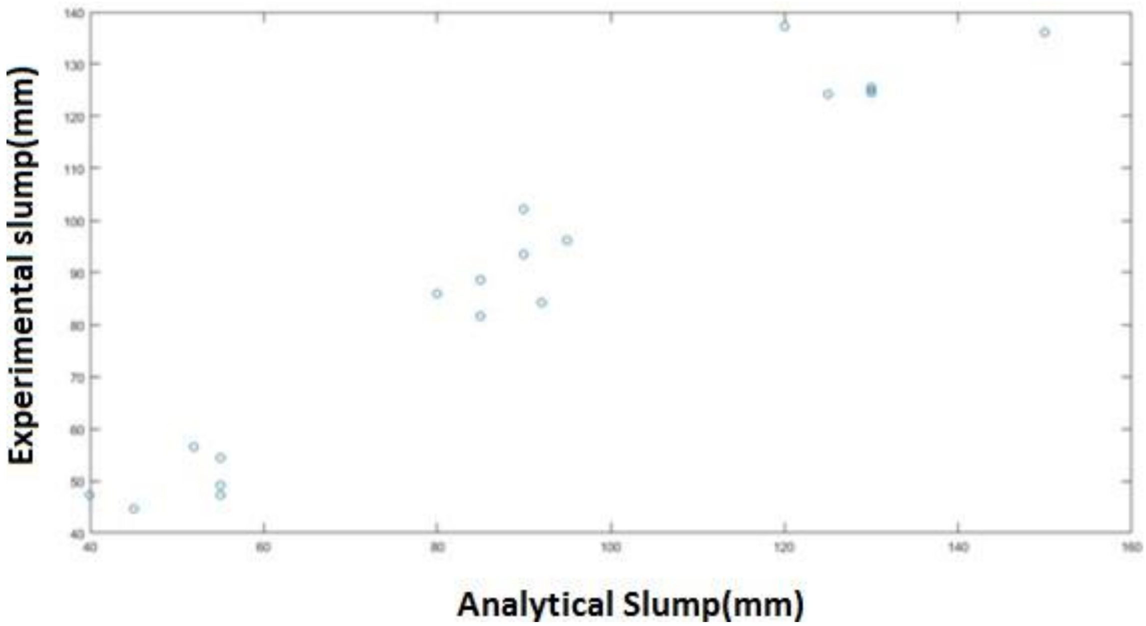


Figure 5.16: Analytical slump values v/s experimental slump values

From fig. 5.15 and 5.16, it is clear that there is a good agreement between the analytical and experimental data. Therefore, the model so developed for optimization of concrete mix design is reliable to great extent.

5.10 OPTIMIZATION

After the experimentation and modeling, optimization is carried out to develop a rational mix satisfying a required strength, slump and cost. The input data for optimization consists of unit cost, the available range and unit weight of each component and all these values are listed in table 5.12 and 5.13.

MATLAB was used for this purpose and 12 constraints were put which are as follows:-

i. Required strength equation (equation 5.1)
ii. Required slump equation (equation 5.2)
iii. Minimum cost equation i.e.

Total Cost = 60(cement) + 1(fly ash) + 10(silica fume) + 50(superplasticizer) + 0.81(fine aggregates) + 0.37(coarse aggregates) + 0(water) equation (5.3)

iv. Absolute volume equation i.e.

1 = cement/3068 + fly ash/2200 + silica fume/2200 + superplasticizer/1090 + fine aggregates/2650 + coarse aggregates/2800 + water/1000 equation (5.4)

v. Lower bound for fly ash

vi. Upper bound for fly ash

vii. Lower bound for silica fume

viii. Upper bound for silica fume

ix. Upper bound for superplasticizer

x. Lower bound to coarse aggregate to total aggregate ratio

xi. Upper bound to coarse aggregate to total aggregate ratio

xii. Lower bound to water binder ratio(0.2 for high strength concrete)

After the constraints were imposed, 3 mixes were tried having 80MPa strength and 120mm slump, 70MPa strength and 80mm strength and 75MPa strength and 50mm slump. The results are mentioned in tables 5.14, 5.15 and 5.16 respectively.

Table 5.12: Component specifications

Component	Unit cost (Rs/kg)	Lower Bound(kg)	Upper Bound(kg)	Specific Gravity(gm/cm^3)
Cement	60	320	600	3.068
Fly ash	1	48	135	2.2
Silica fume	10	16	60	2.2
Superplasticizer	50	5	20	1.09
Fine aggregate	0.81	700	900	2.65
Coarse aggregate	0.37	850	1050	2.8
Water	0	120	200	1

Table 5.13: Component Ratio Constraints

Ratio	Lower Bound	Upper Bound
Water/binder	0.26	0.36
Coarse aggregates/total aggregates	0.52	0.56

Table 5.14: Trial 1

Target strength=80MPa **Target slump=120mm**		
	OPTIMIZATION RESULTS	EXPERIMENTAL RESULTS
Strength	79.9MPa	80.52MPa
Slump	120mm	120mm
Cement	383.127kg	513.65 kg
Fly ash	85.771 kg	96.309 kg
Silica fume	19.1564 kg	32.103 kg
Superplasticizer	5 kg	19 kg
Fine aggregates	900 kg	725.7 kg
Coarse aggregates	1017 kg	883.88 kg
water	120 kg	151.76 kg

Table 5.15: Trial 2

Target strength=70MPa **Target slump=80mm**		
	OPTIMIZATION RESULTS	EXPERIMENTAL RESULTS
Strength	69.956MPa	70.125MPa
Slump	80mm	85mm
Cement	344.206 kg	425.453 kg
Fly ash	76.587 kg	79.77 kg
Silica fume	17.21 kg	26.59 kg
Superplasticizer	8.76 kg	11.25 kg
Fine aggregates	900 kg	793.512 kg
Coarse aggregates	1050 kg	936.116 kg
Water	122.513 kg	145.04 kg

Table 5.16: Trial 3

Target strength=75MPa **Target slump=50mm**		
	OPTIMIZATION RESULTS	EXPERIMENTAL RESULTS
Strength	74.95MPa	75.77MPa
Slump	50mm	55mm
Cement	362.02 kg	440.3 kg
Fly ash	79.0917 kg	82.5 kg
Silica fume	18.101 kg	27.5 kg
Superplasticizer	5 kg	8.5 kg
Fine aggregates	900 kg	783.78 kg
Coarse aggregates	1046.1 kg	939.74 kg
Water	120 kg	140 kg

CHAPTER 6

CONCLUDING REMARKS AND FUTURE SCOPE

6.1 OBSERVATIONS

i. By applying the above mentioned techniques, HPC mixtures can also be prepared with least number of trial mixtures, with desired properties unaffected.
ii. The optimum values of various ratios, most importantly the value of water/binder ratio and fine aggregate/total aggregate ratio have resulted in higher compressive strength at a lower cementitious content resulting in significant cost saving in the concrete production.
iii. Superplasticizer plays a significant role in the attainment of good workable mix at lower water/binder ratios.
iv. There is a good agreement between the computed and the experimental values of compressive strength and slump.
v. The MATLAB model developed in the present work can be used to evaluate mix proportions and the corresponding compressive strength and slump of concrete for varying cement and water/cement ratios.

6.2 FUTURE SCOPE

i. Development of Interactive Website (COST Program)-In the current work, Cost was taken as a constraint but it is limited in several aspects. An interactive website may be developed that takes care of the real world problems and cost of the mix proportion. Using this approach the concrete community would be able to reduce the number of trial batches to a significant extent.

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