DESIGNING AND OPTIMIZING OF CONCRETE MIX PROPORTION USING STATISTICAL MIXTURE DESIGN METHODOLOGY

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By

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ABSTRACT

The primary objective of this thesis is to investigate and explore the feasibility of using statistical mixture experimental design and analysis methods in the optimization of concrete mix proportion and the subsequent prediction of concrete properties. Designing a concrete mixture proportion, which contains several components, such as cement and water content, coarse and fine aggregates, and various additives, to meet several performance criteria, can be a difficult and time-consuming task.

A statistical mixture design approach, which provides a structured design matrix, provides a cost-effective means of concrete performance optimization. In this study, a statistical mixture approach based on an IV-optimal design was applied to investigate the effect of five mixture components (cement, water, coarse aggregates, fine aggregates, and admixture) on key performance criteria, which included the slump, 3-7-28- 56- and 91-day compressive strengths, 3- 7- 28- and 56-day modulus of rupture and the modulus of elasticity. In total, 20 statistically designed concrete mixtures were cast to establish the prediction models for the several performance criteria. The models were developed for mixtures with 372 to 443 kg/m^3 blended hydraulic cement, 155 to 164 kg/m^3 water, 1066 to 1127 kg/m^3 coarse aggregates, 671 to 736 kg/m^3 fine aggregates, and 3.3 to 4.4 liters of high range water reducing agent. The accuracy of the prediction models were validated by confirmation tests for predicted concrete performance. The desirability function methodology was used for simultaneous optimization of multiple responses and determining the optimum binder combinations.

The current research presents a procedure for the successful application of statistical mixture design methodology in concrete mix proportion. The procedure explained in the thesis can be used as a guideline for designing concrete mix proportion for different field application.

As a secondary objective, the results of five mixtures with blended cement from part one, were compared with mixtures of similar proportions but made using ordinary Portland cement. The goal was to compare the differences in compressive strength, flexural strength, and modulus of elasticity gain with time. The results showed that the compressive and flexural strength of blended cement concrete were lower than ordinary Portland cement concrete at early ages. However, the blended cement concrete reached higher strength than conventional concrete after 28-day and onward. The type of cement had no significant effect on the modulus of elasticity.

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List of Symbols and Abbreviations

ACI	American Concrete Institute
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Materials
BDOE	British Department of environment
f'_c	Compressive Strength at 28-day
f_r	Flexural Strength (Modulus of Rupture)
d_i	Desirability Function
D	Overall Desirability
DOE	Design of Experiment
E	Modulus of Elasticity
e	Error term
EVD	Extreme Vertices Design
FA	Flay ash
HRWRA	High-Range-Water -Reducer Admixture
IS	Indian Standard
OFAT	One-Factor-at-a-Time
OPC	Ordinary Portland Cement
PRESS	Prediction Error Sum of Square
R^2	R-square Statistic
R^2_{adj}	Adjusted R-square Statistic

R^2_{pred}	Predicted R-square Statistic
RSM	Response Surface Methodology
SCHSC	Self-Consolidation High Strength Concrete
SF	Silica fume
USBR	United States Bureau of Reclamation
w/c	water/cement ratio
w/cm	water/cementitious material ratio

CHAPTER 1

INTRODUCTION

1.1. General

The proportioning of concrete mixture is a process by which one arrives at an economical and practical combination of concrete ingredients to produce quality concrete. According to Mehta et al. (1993), "This process is considered an art rather than a science". The mix proportioning process largely depends on the engineer who designs the mixture. It highly depends on predetermined requirements such as, the compressive strength and the level of workability, which can be adversely affected by changing the proportion of different components in the mix. Above all, economy has a major role in selecting the suitable ingredients that produce concrete with certain performance characteristics. In this regard, it is clear that the mix proportioning process is the art of balancing the various conflicting demands.

There are many mix proportioning methods around the world. Some of the prevalent methods are; ACI, British Department of Environment (BDOE), United States Bureau of Reclamation (USBR), and Indian standard (IS). All these methods are mostly based on empirical relations, charts, graphs, and tables developed through extensive experiments and investigations using locally available materials. The basic steps in arriving at the proportion of ingredients are the same among these methods but their method of calculation is different. The first step entails specifying the exposure condition, workability of fresh concrete, strength, and durability of the hardened concrete. The second step specifies the maximum and minimum requirements of the specified standard, i.e., maximum water cement ratio (w/c), minimum 28-day specified compressive strength ($f_c^{'}$), minimum air entrained, maximum slump, and maximum coarse aggregates. The third step involves calculating the required water and cement content, coarse aggregates, consequently fine aggregates and required admixtures. All these methods serve as a base to start, the final amount of constituent materials is verified through trial batches based on the consideration of workability and economy. The adjustment for moisture and absorption are made, accordingly.

Usually, in the trial batches phase, a trial-and-error approach is used to adjust the mix proportion. It is typically performed by varying one component at a time while keeping all other constituent materials fixed. This is called the one-factor-at-a-time (OFAT) method in experimentation. By using OFAT in the mix proportioning procedure, no consideration is taken to account for interaction among the concrete ingredients. Due to changing only one factor at a time, the mixtures that are cast and tested are relatively similar. Thus, the chance of obtaining poor results is high, if the initial mixture is ill-chosen.

For traditional normal-strength concrete, a small number of batches can provide reasonable information about the properties of concrete. However, for the new generation concrete, as the cost and number of components increase, achieving an optimized solution needs a systematic plan to alter the factors. The most popular mix proportioning methods used traditionally do not objectively provide the best setting of components to meet desired performance criteria. In addition, sufficient information to obtain prediction equations for different characteristics that can be simultaneously used to obtain optimal combination of the mixture ingredients is not provided. To this end, a systematic approach that provides a guarantee to the best solution, and minimizes the required number of experimental runs without sacrificing the accuracy of the process and results, is needed. Modern statistically based method of experimentation can largely overcome the deficiencies of the current methods. Using this method, the entire experimental process is divided into three stages. A planning stage that entails the use of Design of Experiment (DOE) approach to design the experiment; an implementation stage that conducts the experiment using randomization, replication and blocking principles; and the interpretation stage that involves analyzing the data by statistical methods to draw a meaningful conclusion from the results (Smith, 2005). Applying the statistical method in the mix proportioning of concrete does not change the overall approach of designing the mix proportion using available standards, but it changes the trial batches process (Simon et. al. 1997). It means that the planning stage of experimentation will be modified to use the statistical method to interpret the results and find the optimum mix proportion.

The statistical method of experimentation is based on factorial designs introduced by Fisher in the early 1920s. In this method, unlike OFAT, all factors varies simultaneously to increase the experimental precision and to deal with the interaction, which is important in many engineering applications (Lye, 2002). It reduces the number of tests without sacrificing the accuracy of evaluating effects and the interactions of components. It is widely used in industry and has been applied by some researchers to the mixture proportioning of concrete. However, it is not considered to be a general approach.

Among the different approaches in DOE, response surface methodology (RSM) is used for optimization; where the experiments entail of several factors and the goal is optimization of the responses. There is a special type of RSM called mixture design method in which the factors are the component of a mixture and the response is a function of the proportion of each ingredient. In the case of concrete mix design, the process involves the proportioning of cement, water, fine aggregates, coarse aggregates, maybe supplementary materials, and admixtures. The final product depends on the relative proportions of the components rather than their absolute amount. Therefore, the mixture design method is a rigorous technique to design and analyze the mix proportion and determine an optimized mixture for a given set of constraints.

1.2. Scope

The scope of the current research is to develop an effective and systematic methodology for the design of concrete mixes. A set of twenty trial batches were designed according to the established statistical mixture design method. These trial batches cover a chosen range of proportions for five components of the mix (blended cement, water, high-range-water -reducer admixture, coarse aggregates, and fine aggregates). The selection of the proportion was based on previous data from the literature (see those references denoted by star *). Experiments were conducted and the specimens from the 20 mixtures were tested to measure the slump, the compressive strength, the modulus of rupture (flexural strength), and the modulus of elasticity at specified days. Finally, at the analysis stage, multiple linear regression using ordinary least squares method was applied to fit prediction models which were used to obtain optimal setting of components and to predict desired properties.

According to the standard concrete design codes, a 28-day compressive strength is usually specified, although the strength of concrete can be measured at different ages. Testing at earlier periods such as 3-day or 7-dayis useful for the prediction of the 28-day strength of concrete. Furthermore, the strength gain with time, specifically early-age strength is important in some application of concrete technology especially when supplementary materials like fly ash and silica fume are added to cement. For instance, in slip form applications, knowing the early-strength gain of concrete are crucial to slide or remove the forms. In the current research, blended cement, which is a blended form of general Portland cement, fly ash, and silica fume, is used. It is well-known that adding fly ash to cement results in lower early-age strength. As a secondary objective of the research, the results of five mixtures with blended cement from statistical mixture design are compared with mixtures of similar proportions made with ordinary Portland cement. The investigated properties are the slump, the compressive strength at 3- 7- 28- 56- and 91-day, the flexural strength (modulus of rupture) at 3-7-28- and 56-day, and modulus of elasticity at 3- 7- 28- and 56-day. The goal is to compare the strength gain with time of these two types of concrete and to investigate the effects of these supplementary materials used in the blended cement i.e., fly ash and silica fume on fresh and mechanical properties of concrete.

1.3. Objectives

The main objectives of this thesis can be summarized as follows:

- To use statistical mixture design as a powerful and systematic approach to design concrete mix proportion. This includes :
    - Designing a set of mix proportions to provide adequate and reliable measure of the mean responses
    - Obtaining prediction equations for various performance criteria
    - Obtaining optimal combination of the mixture ingredients using the fitted mathematical models given a set of objectives
- To statistically investigate the rheological and mechanical properties of green concrete containing fly ash and silica fume which includes:
    - Slump
    - Compressive strength gain with time (3- 7- 28- 56- and 91-day)
    - Flexural strength (modulus of rupture) gain with time (3- 7, 28- and 56-day)
    - Modulus of elasticity gain with time (3- 7- 28- and 56-day)
- To compare the above properties for concrete containing blended cement and concrete made with ordinary Portland cement for five selected mixtures.

1.4. Thesis Outline

Chapter 2 is divided in two parts. The first part reviews the most common mix proportioning methods and the research on designing and optimizing the mix proportioning of concrete using statistical mixture design. The second part addresses the use of ternary concrete (made of blended of silica fume, fly ash, and Portland cement), and addresses the preparation of a database from previous research in order to choose acceptable and accurate ranges of components to start the design of mix proportions.

Chapter 3 provides the detailed procedure undertaken to design and optimize the appropriate mix proportioning of concrete using statistical mixture design. The prediction equations are fitted to the measured properties of concrete, and validated using statistical analyses. In addition, the materials and experimental procedures used in this study are presented in this chapter.

Chapter 4 provides a discussion on the effect of each component on the measured concrete properties. The graphical and numerical optimization procedures are explained in detail. The procedure to obtain the optimal combinations of the mixture components using numerical optimization is explained.

Chapter 5 discuses the strength gain of concrete made of blended cement. The properties of five mixtures of blended cement concrete are compared to control mixtures of ordinary Portland cement concrete.

Chapter 6 provides a summary of the overall research work and conclusion. Recommendations for future work are also provided.

CHAPTER 2

REVIEW OF LITERATURE

2.1. Introduction

The first part of this chapter reviews the most common mix proportioning methods and the research on designing and optimizing the mix proportioning of concrete using statistical mixture design. The second part this review focuses on the current knowledge available related to the use of ternary blends concrete i.e. blended cement of ordinary Portland cement and two supplementary materials: fly ash and silica fume. Furthermore, based on an extensive review of the literature (see references denoted by star *) that utilizes fly ash and silica fume in concrete, the range of data properties are gathered and summarized as a base (starting point) for designing mix proportions using the statistical mixture design method.

2.2. Concrete Mix Proportion Methods

Concrete in its simplest form is a mixture of cement, water, fine aggregates and coarse aggregates. Additional components, such as supplementary materials (e.g. fly ash, silica fume, slag) and chemical admixtures (e.g. high range water reducer, air entrained admixture, retarder) may be added to the basic mixture to enhance certain properties of fresh and hardened concrete. Current mix proportioning methods (ACI 211.1 - 1991 R2009, ACI 363 - 1997, BDOE, USBR, IS) provide a procedure for determining a required value of compressive strength at a given age that meets several performance criteria. To illustrate the procedures of these proportioning methods, a summary of the main steps included in each is given in Table 2.1.

Table 2.1 provides some techniques for proportioning a given mixture. However, these techniques do not provide a procedure for finding the best setting of constituent materials to meet several performance criteria simultaneously. They only serve as an initial procedure for achieving the end result in the fewest possible trials. The majority of existing methods for concrete mix proportioning are developed exclusively to proportion concrete to achieve high levels of compressive strength. However, strength properties are not the only desired characteristics of concrete. Generally, each approach requires an initial input in the form of a target compressive strength at a given age. These methods have some common similarity in arriving at the proportions, but they vary in approach, assumptions, and intermediate design steps including the selection of cement content, water content, aggregate content, and workability level to achieve the final mixture proportion (Olek et al., 2002). In addition, in the process of adjusting for individual material characteristic and qualities, the amount of one component changes while all other variables are held constant. Therefore, the variables are tested in sequence rather than in combination. The conventional mix proportioning methods require a relatively large number of concrete mixes, they are insufficient to obtain information on the effect of particular variable on the properties of interest, and cannot detect interaction among variables (Mason et al., 1989). Furthermore, these methods have no proper guidelines for optimizing the mix proportioning of concrete.

Table 2.1.Main Steps Included in Selected Concrete Mixture Proportioning Methods

Steps	Selected Mix Proportioning Methods				
	ACI 211.1-91R2009	ACI 363 R-97	BDOE	USBR	IS
1	Select required compressive strength	Select required slump	Determine free w/c ratio for required strength	Determine free w/c ratio for required 28-day strength	Select required compressive strength
2	Select required slump	Select maximum size of aggregates	Determine free water content required for workability	Estimate water and air content	Selection of w/c ratio from table
3	Select maximum size of aggregates based on required strength	Select coarse aggregates content	Determine required cement content	Estimate percentage of sand in total aggregates	Estimate water and air content
4	Estimation of water and air content and selection of w/c ratio from table	Estimation of free water and air content	Determine total aggregates ratio	Calculation of cement content based on w/c ratio and water content	Estimate percentage of sand in total aggregates (absolute volume)
5	Calculation of cement content	Select w/c ratio from table	Determine fine aggregate content (absolute volume)	Determine total aggregates content to calculate coarse and fine aggregates	Calculate cement content
6	Estimation of coarse aggregates content	Calculate binder content			Determine total aggregate content
7	Estimation of fine aggregates content (absolute volume)	Calculate fine aggregate(absolute volume)			Calculate coarse and fine aggregate
8	Adjustment of aggregates moisture and absorption				
output	Mixture proportions that will produce concrete with a desired level of compressive strength at a given age				
	Trial mixing stage	Trial mixing stage	Trial mixing stage	Trial mixing stage	Trial mixing stage

Therefore, a more systematic approach is necessary to evaluate the effects of multiple variables and to optimize concrete performance by designing a more structured design matrix.

2.3. Optimization Process - Statistical Design of the Experiment

Traditionally, many experimental programs that focus on evaluation of concrete properties are designed such that all but one factor under examination are held constant. This experimental approach is called the "one-factor-at-a-time" approach (OFAT). OFAT is unable to detect interactions among variables or to develop prediction equations for optimization (Lye, 2002). To account for interaction among various components of concrete, and to determine the influence of the mixture composition on the performance parameters as well as the best factor setting for optimizing properties, a multiple-variable experiment should be carefully designed and statistically evaluated. Using statistical principles to design the experiments maximize the efficiency of the trial batches phase by minimizing the number of mixes. It allows useful information to be obtained without testing every combination of variables at every level (Lawler et al., 2005). It also provides an opportunity to use the test results in the development of mathematical models to evaluate and predict expected performance. The statistical approach has the additional advantage that the expected performance parameters can be characterized by an uncertainty measure by means of confidence intervals.

To adequately select the optimum mixture, a complete optimization process that involves several targets and requirements has to be carried out. This involves the selection of experimental variables, objective functions, set of constraints and properly assigned weights (Radlinski and Olek., 2010). In the case of concrete mixture optimization, several approaches have been proposed. These include factorial designs (Basher et al., 1994;Nehdi et al., 2002; Ghezal and Khayat, 2002; Sonebi, 2004; Sonebi et al., 2004; Olek and Lu, 2004), mixture design method (Douglas and Pouskouleli, 1991; Wang & Chen, 1997; Simon et al., 1997,Simon et al., 1999; Ding et al., 1999; Chen et al., 2003; Akalin et al., 2010), response surface method (Rougeron et al., 1994; Bajorski et al., 1996; Simon et al., 1999; Srinivasan et al., 2003; Muthukumar et al., 2003; Nehdi& Sumner, 2004; Murali et al., 2009), Taguchi's approach (Lin et al., 2004; Turkemen et al., 2007; Prabir Kumar, 2008), artificial neural network (Cheng Yeh, 2006; Tao et al., 2006) and genetic algorithm (Lim et al., 2004). Among these methods, response surface method (RSM) and mixture design method appear to be the most popular methods.

2.3.1. Statistical Mixture Design Method

A mixture design is a special type of response surface experiment in which the variables are the components of a mixture and the response is a function of the proportions of the mixture. Application of mixture experiments are found in many areas such as chemical and food industry. The primary differences between a standard response surface methodology and a response surface for mixture approach are in the type of design and in the type of polynomial used for response surface.

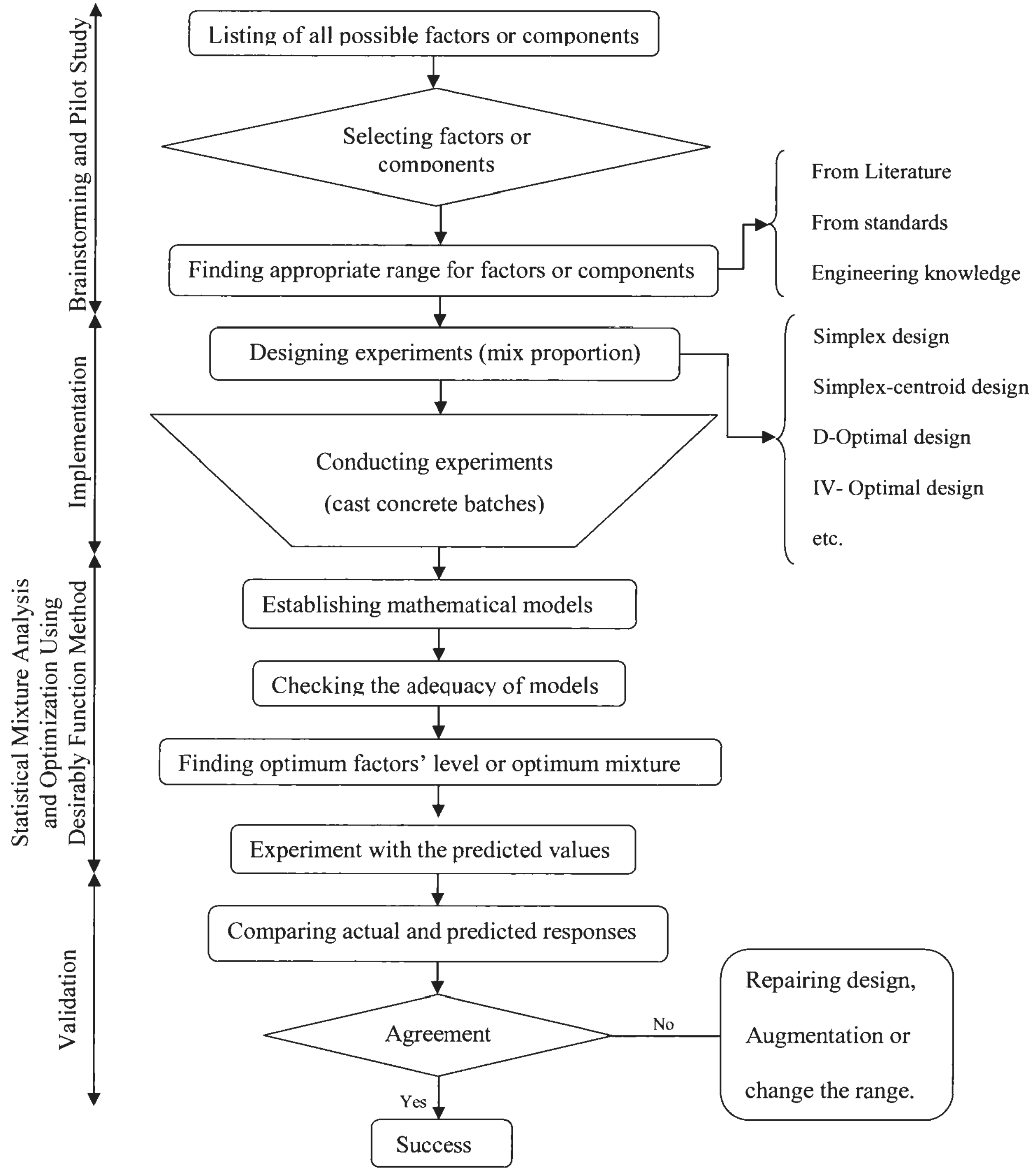

Figure 2.1. Strategy of Experimentation (Adopted and Modified From Anderson and Whitcomb, 2005)

The mixture approach uses (1) special type of design, e.g. simplex design and optimal design. (2) Scheffé polynomial in regression modeling for constructing an empirical model which is slightly different from standard polynomial used in RSM, and (3) a graphical approach based on trace plots for examining the effect of variables (Myers & Montgomery, 2008). In mixture design, unlike RSM, component proportions are treated as dependent variables, which means if one factor increases the proportion of one or more of the other components must decrease in order for the total amount of the mixture to remain constant. Furthermore, the empirical models, which give insight into the behavior of variables (components) and responses (performance criteria) can be used as a tool for understanding the relationship between variables and performance characteristics.

Figure 2.1 illustrates the general strategy for statistical mixture design. It begins with a "Brainstorming and Pilot Study" phase that leads the experimenter to list real factors and related ranges as a starting point. Many experimenters jump too quickly into the test matrix (Implementation phase) and end up wasting time and money on wrong factors with ranges that are either too narrow or wide. Designing experiments listed under the "Implementation Phase" in Figure 2.1 vary all factors simultaneously via cleverly-devised matrices that compute effects with maximal power for predictive modeling. In fact, for a given level of statistical power, statistical methods require far fewer experimental runs than the OFAT approach (Anderson, 2005). "Statistical Analysis Phase" provides superb statistical tools for design and analysis of experiments aimed at process optimization. It consists of a group of mathematical and statistical techniques used in the development of an adequate functional relationship between responses of interest, y, and a number of variables denoted by $x_1, x_2, \ldots, x_n$. This functional relationship expressed as an empirical model fits by least-squares regression and confirmed statistically via analysis of variance (ANOVA). The ultimate goal of mixture design is to construct useful predictive models for all critical responses. Armed with the polynomial equations, specialized software can apply numerical search algorithms that find the most desirable conditions using desirability function methods, known as the "Optimization Phase". However, this recommendation must be validated via confirmatory tests as detailed in the final stage of the strategy for experimentation outlined in Figure 2.1. Scheffé, 1958; Cornell, 2002; and Smith, 2005 provide comprehensive references on the mixture design approach.

For concrete mix design, the classical mixture approach allows the experimental region of interest to be defined more clearly. Using this method, the total amount of all ingredients is fixed (mass or volume) and the factors are proportion of the total amount of mixture. According to the ACI method, the sum of the volume fractions is one. Therefore, concrete constituents are dependent. As such, mixture experiments are more complicated to analyze compared to regular RSM experiments. Hence, it is not widely used in practice (Simon et al., 1997).

2.4. Previous Work on Application of Mixture Design Approach

Standish et al. (1987) showed the possibility of confidently predicting actual porosities of concrete in multi-size systems using regression methods with minimum measurements. A successful application of simplex-lattice design for predicting the porosity of ternary concrete was explained. It was concluded that the method is completely general and can be applied to a mixture with any numbers of components.

Douglas and Pouskouleli (1991) used a statistical simplex-centroid design to investigate the strength development of ternary blended cements composed of Portland cement, ground granulated blast-furnace slag and fly ash (class F, class C). Iso-strength contour plots were utilized to predict the compressive strength of any combination of ternary mortar based on the minimum of seven design points. The special cubic polynomial models were utilized to establish the strength-prediction equations at 1- 7- and 28-day incorporating each class of fly ash. The value of mixture components varied between 0 to100 percent. From the results of the experiments, and based on eleven checkpoints within the experimental boundary, the accuracy of the predicted compressive strength was within 95 percent of experimental values. However, the main weakness of their study is that there are no statistical tests to show that the special cubic model is accurate or a lower order model that can also accurately support the relationships.

Wang et.al (1997) studied the compressive strength of mortar using a simplex-centroid design with the upper and lower bound of Portland cement, fly ash and ground granulated blast-furnace slag. The special cubic models of the compressive strength at 7- 28- and 56-day were derived based on seven design points. The results showed that the contribution of slag on strength gain was more than cement and fly ash at all ages, and the strength prediction equations showed strong interaction between components. Moreover, five more mortars were in order to examine the precision of the predicted models. It was claimed that the simplex-centroid design is more accurate than the entire simplex-centroid design with the minimum and maximum levels in investigating the strength properties of mortar. Similar to the work of Douglas et al. (1991), that research does not take into consideration the possibility of lower order models to predict the concrete properties.

Simon et al. (1997) applied statistical mixture design methodology to optimize high performance concrete mix proportion. Six mixture components were selected: Type I/II Portland cement, water, silica fume, course aggregates, fine aggregates, and high-range-water-reducer admixture (HRWRA) in terms of volume fraction for non-air entrained concrete. A modified-distance design that included the extreme vertices and centroids were used to construct the design space with different constraints. Each constraint of the components was selected so that the volume fractions sum to unity. The quadratic Scheffé polynomial with 21 coefficients was applied to construct the prediction equations of six components. The researchers ran 36 mixtures including 21 mixtures to estimate equation coefficients, 5 mixtures as replications, 7 mixtures to check the adequacy of the models and finally 3 mixtures to check the fabrication and measurement process. The properties of interest were: slump, 1- and 28-day compressive strength, 42-day rapid chloride test, and cost. By converting the volume fraction to weight using the specific gravities and percent solids, all mixtures were cast and the results were analyzed using analysis of variance (ANOVA). According to their research, a quadratic model was chosen because of the variation of the materials and conditions by location, although the experimental runs were increased. The adequacy of the models was verified by checking the ANOVA assumptions: normality, constant variance, and randomization. The results were interpreted using trace and contour plots. The results of the experiments showed that a linear model can fit the slump and 28-day compressive strength, while a quadratic model can describe the characteristic of the 1-day strength. The natural logarithm of a linear model fitted well to the rapid chloride test. In the final part of the study, numerical optimization using desirability functions was applied to find the optimum mix. The uncertainty of the fitted functions was characterized by the 95% confidence interval. In conclusion, the researchers argued that in the presence of many components and several properties of interest traditional trial-and-error methods can easily miss the optimal conditions, resulting in higher costs over the long term. They concluded that the mixture approach provides the proper framework for optimizing high performance concrete.

Two years later, Simon et al. (1999) described, in detail, the statistical mixture approach and response surface method for the mixture proportioning of high performance concrete. They explained that rather than selecting one starting point like ACI 211.1, a set of trial batches could cover a chosen range of proportions for each component. This means that the statistical methods do not change the overall approach of mix design, but they would change how trial batching is conducted. In the second part of the article, the major steps of mix proportioning in a traditional response surface approach are described. These steps include defining performance criteria, selecting materials, selecting variables, defining variables' ranges, designing and conducting the experiments using statistical principles, analyzing the results, fitting the model, and validating them. The authors claimed that the traditional RSM is more popular than the mixture approach because the results are easier to use and the interpretation is more straightforward.

Tong Ding et.al. (1999) adopted an extreme Vertices Design Method (EVD) to establish the performance equation of concrete with a multi-component binder system. This method is a specific type of mixture design method including all vertices, the centroid of the entire experimental space, and the centroids of the boundary surfaces. The effect of three components – Portland cement, fly ash, and natural zeolite powder on 7- and 28-day compressive strength of concrete was studied. Nine experimental points were chosen by

EVD, and three additional experiments were conducted to validate the models. A cubic polynomial was fitted to relate compressive strength and binder compositions using the least squares method. The results indicate that the models are able to predict the responses with less than 6% error, and all results were in agreement with the literature. As such, it was claimed that using limited experimental points and statistical analysis can accurately predict the compressive strength of the concrete with combined mineral admixtures.

Chen et al. (2003) investigated the feasibility of applying the simplex-lattice design for prediction of cement-based composite properties. They explained how to use pseudo-component to define a coded value between 0 and 1 over the feasible region, which made model fitting easier over the constrained region. A simplex lattice design was applied to study the compressive strength at 7- and 28-day. The mixtures were composed of cement, silica fume, and fly ash. According to their finding, a 3^{rd}order regression model was suitable to establish the relationships. The models fitted using the least squares method showed the rationality of using nonlinear relationship between compressive strengths and binder proportions. The precision of predictions were within a 95% prediction interval. In order to decrease the cost and the required tests, 1^{st} or 2^{nd}order models were fitted to the measured data. Nonetheless, the result of statistical F-test in the paper showed that lower-order model could not replace 3^{rd}order model. Generally, lower order regression models are preferred over higher order models unless the former cannot produce accurate predictions. The authors concluded that this method can provide global optimal points, which can be one or more points or be a plane rather than local optimal points provided by other kind of designs such as orthogonal designs.

Muthukumar et al. (2004) and Barbuta et al. (2008) attempted to optimize polymer concrete mixture using the mixture design approach. Second order polynomials were applied to investigate the effect of three factors on the performance properties of polymer concrete. Analysis of Variance technique was employed to show the significance of the selected models.

Yeh (2009) combined three methodologies (flattened simplex-centriod mixture design, artificial neural network and mathematical programming) to optimize the mixture proportion of concrete containing fly ash, slag, and superplasticizer. The author claimed that the combination of these methods can reduce the number of test mixes without sacrificing the accuracy of evaluating effects and interactions.

Akalin et al. (2010) [a] demonstrated the effect of admixture components and admixture dosage on the mortar properties using statistical mixture design method. The primary aim was to investigate the effect of admixture dosage on properties of concrete and to study the effect of admixture types. As such, the amount of cement, water, and sand were kept constant. The admixture dosage was investigated at three levels. The 2^{nd} degree Scheffé polynomial was applied to derive the quadratic empirical models to study the effects of components on water reduction and 1-, 7- and 28-day compressive strength of mortar. A computer-generated D-optimal design with 54 runs was used to design the experimental space and to study the effect of responses. The adequacy of the obtained models was checked using lack of fit test and p-value test at the 95% confidence level. Trace plots were employed to examine the individual effects of each component. The results revealed that in addition to the admixture type, the dosage of each admixture had significant effects on the properties of mortar. Since the main purpose of statistical mixture design is optimization, the desirability function approach was used to optimize multiple responses simultaneously at the lowest price.

Another study by Akalin et al. (2010)[b] conducted a series of experiments in which a statistical mixture design approach was used to optimize an eight-component Self-Consolidating High Strength Concrete (SCHSC) mixture subject to several performance constraints. According to the paper, the D-optimal design with upper and lower bound of component proportions was adopted to study fresh and hardened properties of SCHSC. Those properties were slump flow by Abrams' cone, T50 slump flow time, appearance, unit weight, 1- 7- and 28-day compressive strength, and rapid chloride penetration. The concretesmixes were made with cement, water, silica fume, pulverized fly ash, natural sand, crushed sand, aggregates between 5 to 12 mm, and admixture. 46 experiments were concluded and a 2nd -degree Scheffé polynomial was chosen for fitting regression models to the data using the D-optimal design. A computer-generated D-optimal design was selected because of an irregular shape of the experimental region. Standard response surface designs such as simplex-lattice and simplex-centroid design were not applicable because of additional constraints on the component properties. The adequacy of the obtained models was verified using lack of fit test and p-value test at the5% significance level. Trace plots were used to assess the effects of mixture components on responses. The desirability function approach was used to optimize all responses simultaneously. A mixture with the same material after 5 months was prepared to verify the accuracy of the predicted responses under reasonably similar experimental conditions. The results of verification tests were in good agreement with predicted responses, except for slump flow and T50 slump, which depended on environmental conditions rather than solely being a function of mixture proportions.

2.5. Blended Cement Concrete of Fly Ash and Silica Fume

Since the 1950s a considerably large and continually growing body of literature addresses the ternary-blended concrete of ordinary Portland cement, silica fume and, fly ash (Berry, 1980). Nowadays, application of this kind of concrete is more popular because of the ecological benefits resulting from utilizing these industrial by-products, and the benefits achieved in terms of overall economy. According to Malhotra (2002) using fly ash in concrete has significant environmental benefits. Producing one tonne cement can release around one tonne of CO_2. If the amount of cement, as an expensive component of concrete, can be reduced and replaced with low price materials such as fly ash, it not only reduces the cost of concrete production but also significantly reduces greenhouse gas emission.

2.5.1. Blended Cement Concrete of Fly Ash and Silica Fume

According to the literature, ternary blended cement made with Portland cement, fly ash, and silica fume offer significant benefits over binary cement, and even greater enhancement over straight Portland cement (Olek et al., 2002; Nochaiya et al., 2010; Muthupriya et al., 2011; Hariharan et al., 2011). Nehdi (2001) points out the advantage of particle packing; it improves the density and reduces the pore structure of concrete. This increases the compressive strength and increases the resistance to chloride penetration. Radlinski and Olek (2010) state that an increasing interest of ordinary Portland cement, fly ash, and silica fume (OPC/FA/SF) mixture is frequently attributed to synergistic effects of this ternary system.

Fly ash acts as an inert component at its early ages and it has a minor contribution in hydration; however, fly ash contributes to strength development as it matures (Olek et al., 2002). Silica fume, which has a high content of very fine and reactive silicon dioxide (SiO_2), improves the early age performance of concrete. It compensates for the slow pozzolanic reactivity of fly ash in early ages (Barbhuiya et al., 2009; Nochaiya et al., 2010). The inclusion of silica fume is found to significantly increase the early ages and 28-day compressive strength of fly ash concrete. A possible explanation for this effect might be due to the pozzlanic reaction of silica fume with $Ca(OH)_2$ from the hydration of cement. It is also possible that the micro-filler effects of extremely fine particles of silica fume strengthens the interfacial transition phase concrete.

Khatri et al. (1995) and Nochaiya et al. (2010) conducted series of experiments in which they investigated the different hardened properties of ternary blend concrete. Their results showed that compressive strength of concrete containing the combination of ordinary Portland cement, silica fume, and fly ash produce higher compressive strength at 28-day compared to only Portland cement concrete. However, ternary mixtures containing both fly ash and silica fume reached lower strength compared to ordinary Portland cement concrete at 3- and 7-day. The result of experiments by Bouzoubaâ et al. (2004) showed that the inclusion of silica fume in fly ash concrete at water to cementitious material ratio (w/cm) of 0.40 and total cementitious material (cm) of 350 kg had no significant contribution on increasing the 1-day compressive strength. As such, it was claimed that the silica fume cannot be used to overcome the adverse effect high fly ash content on the

1-day compressive strength of concrete. The results showed significant increases in 7-28- and 91-day compressive strength of ternary concrete. Unlike the first part of the experiments, the results demonstrated that at w/cm = 0.35 and cm = 450 kg, the incorporation of silica fume did not enhance the compressive strength of concrete even at later ages.

Khatri et al. (1995) in the second part of their research stated that the flexural strength and elastic modulus of ternary blends increase due to the addition of silica fume and fly ash. However, all gains in flexural strength and elastic modulus were found to be proportional to the compressive strength gain.

Adding silica fume decreases the flowability of concrete due to its very fine particles and greater surface area that increases water demand (Nawy, 2001). Introducing fly ash leads to partially enhanced workability and cohesiveness due to its spherical particles and glassy texture, which reduce inter-particle frictions (ACI 232.2R-03; Nochaiya et al., 2010). Barbhuiya et al. (2010) confirmed this characteristic of silica fume. Two series of experiments were conducted, where 30% and 50% of cement replaced with fly ash at constant water to binder ratio of 0.35. In terms of fresh properties, the results showed that the addition of silica fume to fly ash concrete decreased workability, but superplasticizer helped to gain acceptable workability. Moreover, a study by Bouzoubaâ et al. (2004) showed that the required dosage of HRWRA in ternary blends decreased with increasing fly ash content and decreasing silica fume content. In general, fly ash increases the setting time of concrete, and adding silica fume to the fly ash concrete partially decreases this setting time, depending on the percentage of fly ash, but the results revealed that the use of silica fume in fly ash concrete has no significant effect on reducing the setting time.

Finally, from an economic point of view, the relatively low cost of fly ash offsets the increased cost of silica fume (Thomas et al., 1999).

2.6. Mixture Components of Blended Cement Concrete containing Fly Ash and Silica Fume

To use the mixture design method, minimum and maximum levels of each component must be defined. These ranges can be either selected according to the available mix proportion methods or to the typical volume fraction (the mass fraction) of the fly ash and silica fume concrete. The data collected from the literature can be a starting point. In the current study, the volume fraction is used to define the appropriate components' range. To this end, an extensive review of publications that used silica fume and fly ash as cementitious materials were collected to create a database (References with * symbol). Most reviewed papers evaluate the proportioning containing ternary concrete with fly ash and silica fume specifically for high performance concrete (high strength concrete).

By extracting the relevant information in the literature, a database of 267 concrete mixtures was compiled. The ranges of collected data, in the compiled database, are for cement content, water content, total cementitious material, water cementitious material ratio, coarse and fine aggregates content, silica fume, and fly ash content. The properties collected are slump, compressive strength, flexural strength (modulus of rupture), and modulus of elasticity. It should be noted that none of these properties are reported for every concrete mixture found in the literature; also, the durability properties are not included in this review as it is outside the scope of the current research. Table 2.2 summarizes the data reported in the literature for each of the main constituent materials including the water binder ratio. The overall range of components and the mean value are given for each constituent.

Table 2.2. Summary of Reported Constituent Materials in Blended Cement Concretes

Constituent Materials	Most frequent range	Overall range	mean	Frequency of constituent material in the papers
Total cementitious material (kg/m^3)	350 - 450	197 - 648	387	191 out of 267
Water content (kg/m^3)	140 -160	104 - 215	158	152 out of 267
Water binder ratio	0.30 – 0.45	0.27 - 0.80	0.40	250 out of 267
Coarse aggregates (kg/m^3)	1000 – 1200	971 - 1441	1125.5	149 out of 267
Fine aggregates (kg/m^3)	600 – 800	355 – 900	681	149 out of 267
Silica fume percentage	4% - 6%	2.5% - 20%	8%	227 out of 267
Fly ash percentage	10% - 25%	5% - 6.5%	26%	233 out of 267

2.6.1. Total Cementitious Material Content

From Figure 2.2 the total cementitious content of OPC/FA/SF mixtures that are reported in the literature ranged from 197 to 648 kg/m^3; however the most commonly used amounts ranged from 350 to 450 kg/m^3. The most common total binder reported is 400 kg/m^3.

2.6.2. Water Content

As illustrated in Figure 2.3, water content of the mixture reported in the literature vary from 100 to 220 kg/m^3, with the common water content of 140 to 160 kg/m^3.

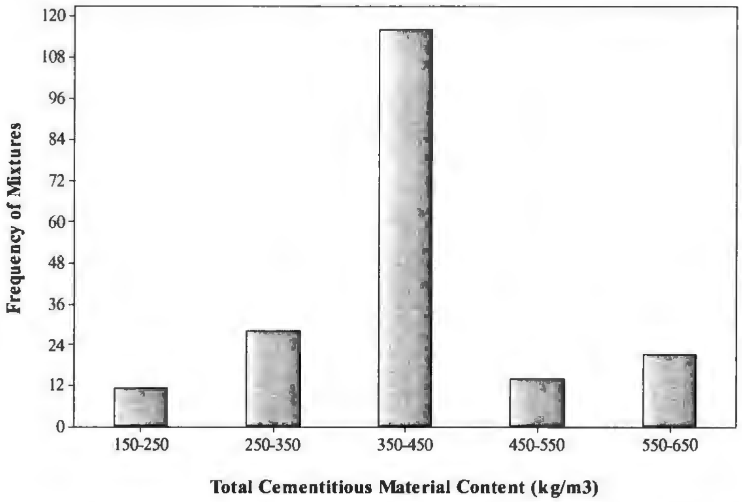

Figure2.2. Frequency of Total Cementitious Materials in Blended Cement Concretes

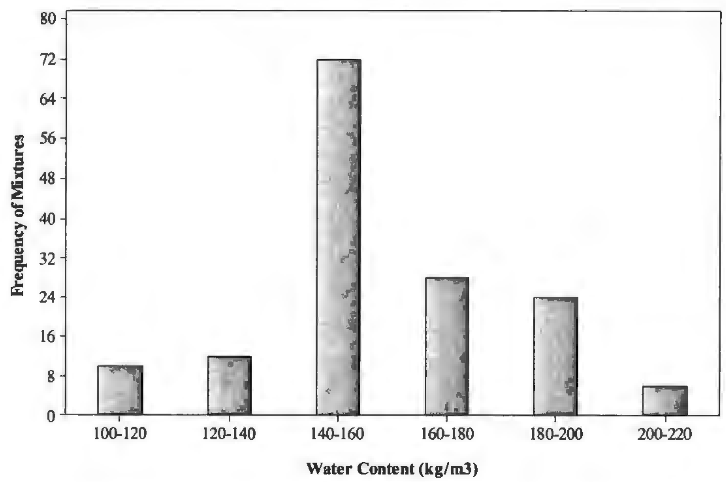

Figure 2.3.Frequency of Water Content in Blended Cement Concretes

2.6.3. Water-Cementitious Materials Ratio

Figure 2.4 illustrates the water-cementitious material (w/cm) ratio. The w/cm is an important indicator of the quality of the concrete. It controls the compressive strength and the permeability of concrete. According to many references, the w/cm ratio and strength relationship of concrete can be explained as the natural effect of a progressive weakness of the concrete matrix by increasing porosity by increasing w/cm ratio (Kosmatka et al., 2003). As can be seen in the Figure 2.4, the w/cm ratio utilized in ternary concretes ranged between 0.30 and 0.45, which are lower than those of conventional concretes.

2.6.4. Coarse and Fine Aggregates Content

Figures 2.5 and 2.6 show the frequency of coarse and fine aggregate content in blended cement concrete. Generally, aggregates occupy 60 % to 75 % of concrete volume. The actual amount is influenced by fresh properties, hardened properties, construction applications, and economy (Kosmatka et al., 2003). As can be seen in Figure 2.5, coarse aggregates content varies from 970 to 1440 kg/m^3, while most of the mixtures contain 1000 - 1200 kg/m^3. In the vast majority of the studies fine aggregates range between 600 and 800 kg/m^3 as shown in Figure 2.6.

It is well known that using well graded materials results in less concrete shrinkage, greater strength, less permeability, and enhance finishibility. According to the literature, the most frequently used size of coarse aggregates is either 10 or 20 mm; although the coarse aggregates gradation differs according to construction application and type of concrete.

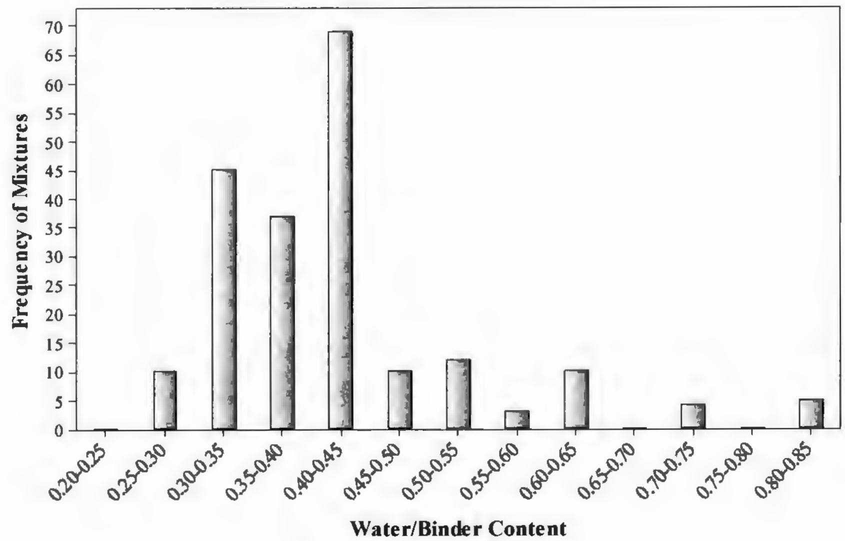

Figure 2.4. Frequency of Water-Cementitious Material Ratio (water- binder) in Blended Cement Concretes

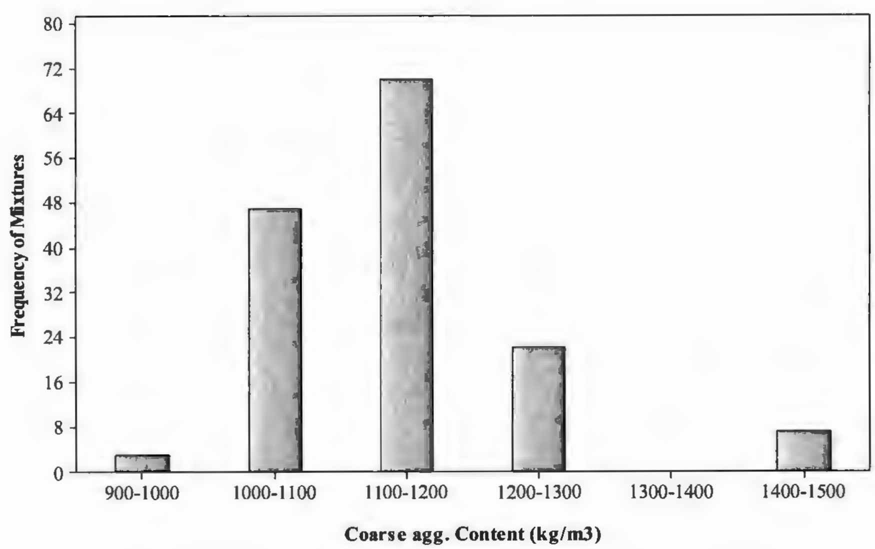

Figure 2.5. Frequency of Coarse Aggregates Content in Blended Cement Concretes

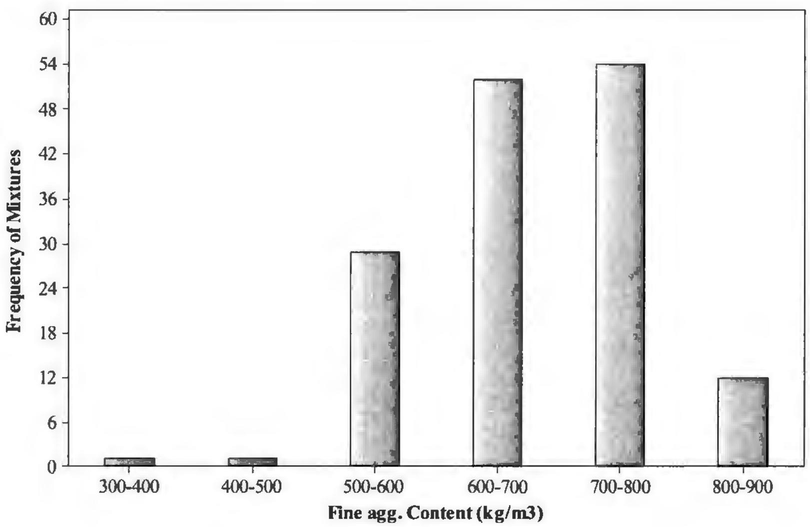

Figure 2.6. Frequency of Fine Aggregates Content in Blended Cement Concretes

2.6.5. Silica Fume and Fly Ash Percent

Silica fume content varies from 2 to 20 % by mass of binder (Figure 2.7).Nonetheless, in most cases it ranges from 4 to 12 %, with 4 to 6 % being the most prevailing value. Fly ash content reported in the literature ranges from 5 to 70 %, with the most frequent being 20 to 35 % as shown in Figure 2.8.

Bauzoulaa et al. (2004) stated that the use of both fly ash and silica fume appear to be beneficial for reducing plastic shrinkage, and chloride-ion penetrability. In addition, the use of silica fume contributed significantly to decrease the sensitivity of curing mode of fly ash concrete.

Regarding the optimum content of fly ash and silica fume, some recommendations have been established with respect to different properties of concrete. Nehdi and Sumner (2002) suggested that using silica fume in ternary OPC/FA/SF is not economical beyond levels of about 3-5 % with respect to rheological, mechanical, durability, and economy. In addition, it was stated that using more than 30 % of fly ash and more than 10 % of silica fume dramatically decreases the desirability function during numerical optimization. Olek et al. (2002) recommended the incorporation of 5 to 7 % silica fume and 25 to 30 % fly ash to obtain promising performance. Later, Olek et al. (2010) state that the optimum mixture should contain 20 % fly ash and 7 % silica fume based on the selected weight coefficients for each performance criteria. Regardless of the predefined weights, the optimum mixture always contains 20 % fly ash rather than 30 %.

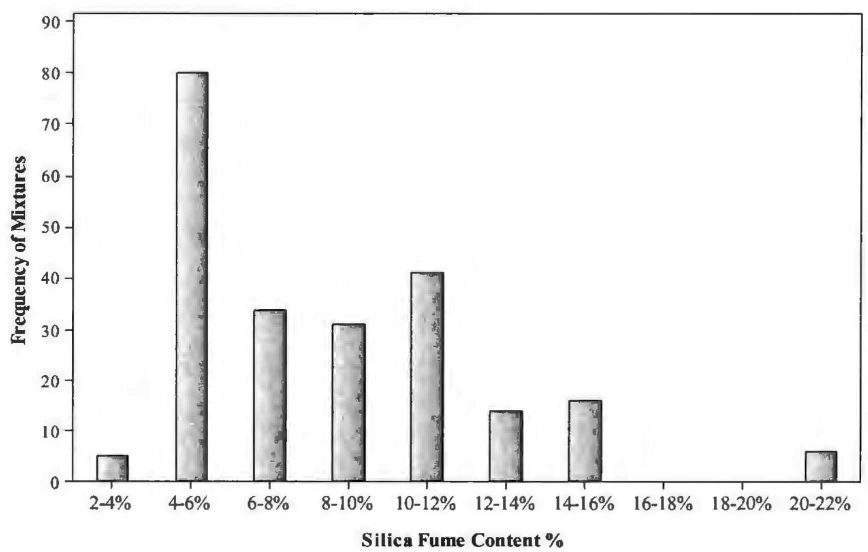

Figure 2.7. Frequency of Silica Fume Percent in Blended Cement Concretes

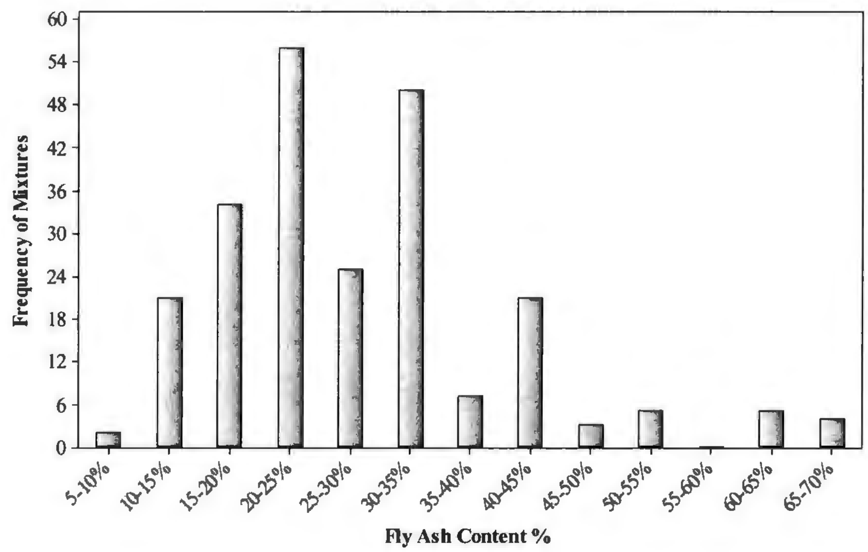

Figure 2.8. Frequency of Fly Ash Percent in Blended Cement Concretes

In the optimization process performed by Lawler et al. (2005), the mixture containing 25% class C fly ash and 5 % silica fume displayed promising strength gain and improved modulus of elasticity. This mixture ranked slightly lower than the mixture with 15 % class C fly ash and 5 % silica fume. In conclusion, and according to the database, it can be stated that the optimum levels of fly ash and silica fume to obtain reasonable strength development and durability are between 20 - 25% and 5 – 8 %, respectively.

2.7. Properties of Blended Cement Concrete Containing Fly Ash and Silica Fume

Among the different concrete properties that have been reported in the literature, the properties available included in the current database are slump, 1- 3- 7- 14- 28- 56- and 90- day compressive strength, 7- 14- 28- and 56-day flexural strength (modulus of rupture), 28- and 56-day modulus of elasticity and air content. The compressive strength gain is the most frequently reported property of concrete that has been investigated when examining the effect of cement replacement by fly ash and silica fume. This is partially for the reason that it is easy to perform and to some extent because many, though not all of the properties of concrete qualitatively can be related to its strength. The 7-day and 28-day compressive strength are the most commonly reported properties. 1-day and 3-day compressive strength are recorded less, and 14- 56- and 90-day compressive strength are reported even less than 1- and 3-day.

According to Mehta and Monteiro (2005), workability is not a fundamental property of concrete. Workability is related to the type of construction, method of placing, compacting, and finishing. Inappropriate workability may have significant bearing on the performance of hardened concrete due to compaction difficulties. It has been stated that the long-term performance of concrete is significantly affected by the degree of its compaction. Due to the composite nature of workability, there is no single test available to measure workability. Specifically, the most universally used test is the slump test, which measures the consistency of concrete, which provides indirect information for workability of concrete. Workability, in terms of slump is the next most frequently property that is measured.

The modulus of elasticity is one of the most important mechanical properties of concrete. In spite of the nonlinear behavior of concrete, an estimate of the elastic modulus is necessary to determine the stresses induced by the strain associated with environmental effects. Only 28 and 56-day modulus of elasticity is measured in the few numbers of papers, and there are no information related to early age modulus of elasticity in the reviewed papers.

Flexural strength of concrete, which is reported as a modulus of rupture, is generally assumed to be about 10 to 20% of compressive strength. Mehta and Monteiro (2005) stated that it may be correct as a first approximation but it may not always be the case. It was stated that this relationship might be influenced by different factors such as different test methods, quality of the concrete, aggregate characteristics, supplementary materials and admixtures in concrete. Despite the importance of flexural strength especially in designing for serviceability of structures, it is reported at 7- 14 and 28-day for less than 10 % of the recorded mixes in the database. In addition, only in two mixes, results of 56-day flexural strength are recorded among 267 mixes. This is because the flexural test is not convenient for quality control or compliance purposes. A summary of data reported in the literature is included in Table 2.3. This table includes the performance levels of blended cement concrete that covers the overall range of values and mean value for each performance characteristics.

Since there is few information regarding flexural strength and modulus of elasticity gain with time, the research will investigate this properties at 3- 7- 28- and 56-day, in addition to the compressive strength at 3- 7- 28- 56- and 91-day, and slump. The statistical mixture design methodology is used to design and optimize the mix proportions with the as low as possible number of trail batches. The empirical models will also be developed for future prediction and optimization of measured performance criteria, and for observing numerical effects and interactions among mixture components, which cannot be observed by trial-and-error approach.

Table 2.3. Performance Properties of Blended Cement Concrete

Properties	Most frequent range	Overall range	Mean	Frequency of constituent material
Slump (mm)	80-120	10-228	89	177 out of 267
1-day compressive strength(MPa)	9-19.8	1.8-43	16.8	130 out of 267
3-day compressive strength (MPa)	16.4-30	5.10-74.1	25.1	136 out of 267
7-day compressive strength (MPa)	23-37.5	8.4-73.3	33.6	209 out of 267
14-day compressive strength (MPa)	26-45	22.07-66.5	41.6	98 out of 267
28-day compressive strength (MPa)	38-60	16.6-92.6	47	230 out of 267
56-day compressive strength (MPa)	45-67.5	27.5-96.59	59.4	92 out of 267
91-day compressive strength (MPa)	52.5-67.5	29-84.30	59.2	81 out of 267
28-day Modulus of elasticity (GPa)	31-35.9	21.8-42.2	32.7	24 out of 267
56-day Modulus of elasticity (GPa)	34.1-38.6	25.30-41.4	34.6	19 out of 267
7-day flexural strength (MPa)	2.5-4	2-6.1	3.5	20 out of 267
14-day flexural strength (MPa)	3.5-5.4	2.8-6.9	4.4	23 out of 267
28-day flexural strength (MPa)	5.8-5.9	5.36-7.4	5.9	8 out of 267
Air content %	6-7.5	1.4-11.3	6	163 out of 267

CHAPTER 3

PRACTICAL ASPECTS OF USING STATISTICAL MIXTURE DESIGN APPROACH

3.1 Introduction

As explained in the previous chapter, traditional methods of developing mix proportions of concrete are based on changing one factor at a time while holding the other factors constant. This method is inefficient, costly and requires a large number of trial mixes to develop an optimized mixture. To this end, applying the systematic statistical approach of mixture design to designing the experiments maximizes the efficiency of the trial mixes. The interaction between various components of the concrete mixture can be accounted for, and the number of trial mixtures required for developing the desired mix proportion can be minimized. The results of the experiments can be used to develop mathematical models to predict and optimize the expected performance.

In this chapter, the procedure to design the appropriate mix proportioning of concrete using statistical mixture design is explained in detail. The 28-day compressive strength is used as an example for response of interest to illustrate the methodology. The procedure involves the following steps, explained in details later in this chapter.

1. Performance criteria
2. Selecting materials
3. Identifying variables

4. Defining variables' ranges

5. Designing and conducting the experiments using a mixture design approach

6. Analyzing the results

7. Fitting the models

8. Optimizing and validating the models

3.2 Defining Performance Criteria

The first step in the planning process is defining the performance criteria to be met. There are many possible performance criteria that can be defined for a concrete mix design. For the purpose of explaining the statistical procedure, the following properties, Table 3.1, of concrete are sought.

Table 3.1.Optimum Properties of Interest

Performance Criteria	Desired Values
Slump (mm)	50 - 100
3-day compressive strength (MPa)	26 - 33
28-day compressive strength (MPa)	50 - 65
56-day compressive strength (MPa)	62 - 70
28-day modulus of rupture (MPa)	6 - 7.3
28-day modulus of elasticity (GPa)	32 - 34

3.3. Selection of Materials

The main concern in the selection of materials is to ensure that the performance criteria can be met using these materials. In this research, the following materials are used for the production of concrete mixtures.

3.2.1. Cement

Two types of cement (blended cement and ordinary Portland cement) are used in this study. The blended cement produced by Holcim (Canada) Inc, meets the requirements of ASTM C595 / 595M - 12. It is anecologically-safe cement that is a triple blend of Portland cement, fly ash, and silica fume. It contains 25 % fly ash, 5 % silica fume, and 70 % Portland cement. According to the database developed in Chapter 2, the percentage of fly ash and silica fume in this type of cement is consistent with the optimum percentage of these two supplementary materials in ternary blend concrete.

The ordinary Portland cement meets the requirements of ASTM C150 / C150M – 12.The composition and physical characteristics of these cements are presented in Table B.1 of Appendix B.

3.2.2. Aggregates

The coarse and fine aggregates are supplied from locally available sources. The Coarse aggregates are mostly crushed stone of granite, with a maximum nominal size of 20 mm. The fine aggregates are of the same source of coarse aggregate with a finesse modulus of 2.65. Sieve analysis of the aggregates is conducted in accordance with ASTM C136 - 06.

Tests of specific gravity and absorption percentage are carried out according to ASTM C127 - 12 and ASTM C128 - 12, respectively. The results of sieve analysis are plotted, with the limits specified in CSA - A23.2, for coarse and fine aggregates as shown in Figures 3.1 and 3.2. The grading of coarse and fine aggregates and the selected physical properties are given in Tables 3.2 and 3.3, respectively.

Table 3.2. Grading of Aggregates

Aggregates	Sieve size											
	40 mm	28 mm	20 mm	14 mm	10 mm	5 mm	2.5 mm	1.25 mm	630 µm	315 µm	160 µm	80 µm
Coarse	-	100	96	68.7	39.8	8.0	1.3	-	-	-	-	-
Fine	-	-	-	-	100	99.7	85.7	66.5	46.5	26.5	10.3	3.3

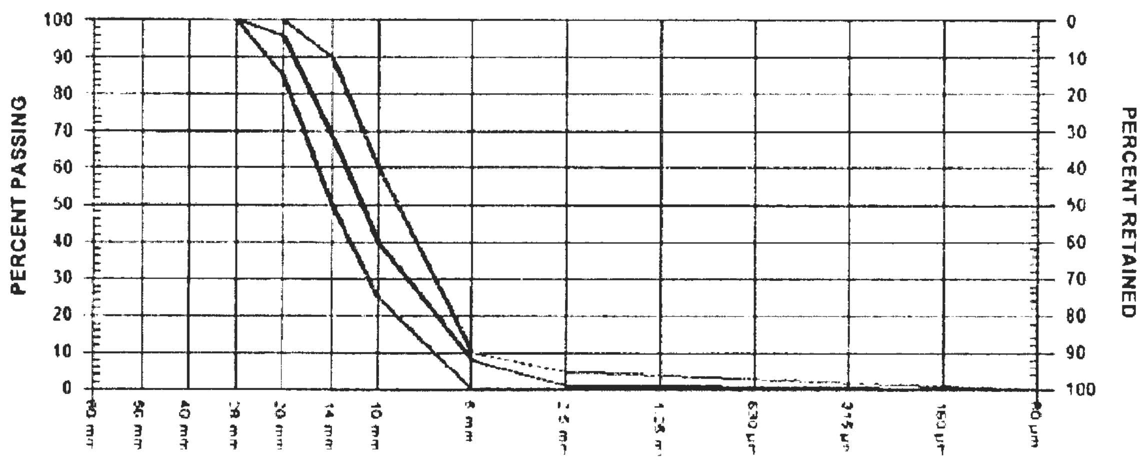

Figure 3.1.Grading of Coarse Aggregates

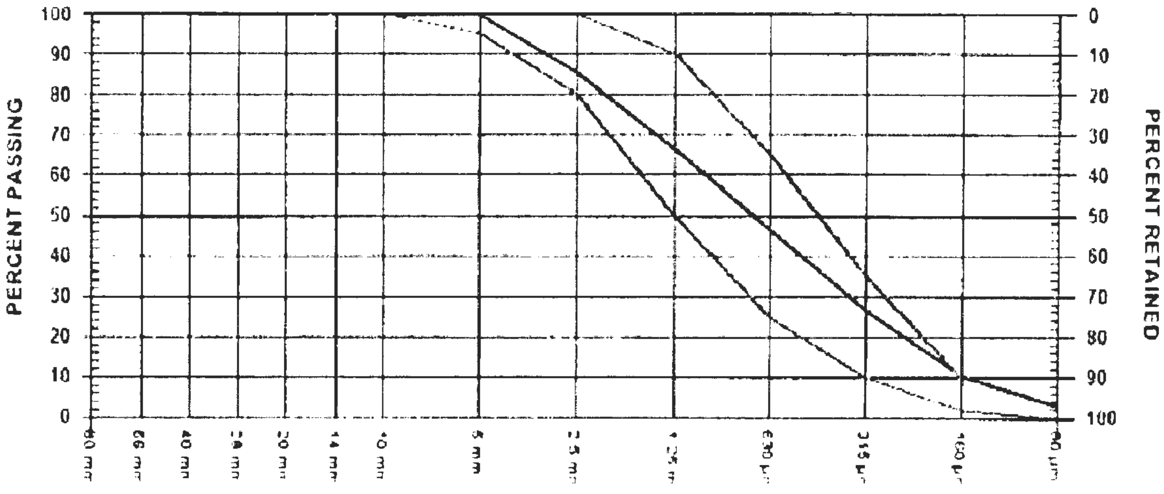

Figure 3.2. Grading of Fine Aggregates

Table 3.3. Physical Properties of Aggregates

	Coarse aggregate	Fine aggregate
Apparent specific gravity	2.62	2.62
Absorption, percentage	0.7	1

3.3.3. Chemical Admixture

For the entire experimental program a high range water reducing admixture (HRWRA), ADVA 140M, is used. It has apolycarboxylate base and complies with the requirements of ASTM C 494 type A and F.

3.4. Selection of Proportion and Constraints

The selection of variables depends on the overall goal of a project and the budget allocated to mixture proportioning (Simon et al., 1999). The number of variables is crucial to the statistical mixture design. Adding each component increases the number of tests required to build the mathematical models. In this study, five mixture components are considered in the design of the mixture proportions. These components are cement(x_1), water(x_2), coarse aggregate (x_3), fine aggregate (x_4) and HRWRA (x_5). Air content is not considered as a component. Although ignoring air as a variable changes the volume fraction, it can be neglected when dealing with small batches.

The selection of appropriate ranges is important because setting too wide ranges may result in the failure to identify the best mixture and setting too narrow ranges may result in inability to simultaneously meet all performance criteria (Simon et al., 1999). The minimum and maximum levels of each component are chosen according to ranges found in the literature review, in Chapter 2, with constraints that the volume fractions sum to unity. In addition to the individual constraints on each component, the mortar fraction of concrete (water, cement, and fine aggregates) ranges between 50 % and 65 %, by volume fraction, to improve consolidation (Kosmatka et al., 2003).The coarse-to-fine aggregates ratio is assumed to range between 1.5 and 1.7.

To design the mixture proportions, it is easier to consider the relative proportion of the components by volume fraction rather than by weight, and then convert the volume fraction to its corresponding weight using the specific gravity. The five components, their volume and mass fraction ranges are given in Tables 3.4 and 3.5, respectively.

3.5. Experimental Design Details

As explained earlier, in the mixture experiment approach, the measured responses are assumed to depend on the proportion of materials present in the mixture rather than on the amount of mixture. In general, in a mixture with q-components where x_i represents the proportion of the i^{th} ingredient in the mixture, the relation between variables is:

$$\sum_{i=1}^{q} x_i = x_1 + x_2 + x_3 + \ldots + x_q = 1 \qquad [3.1]$$

$$x_i \geq 0, \qquad i=1, 2, 3, \ldots, q$$

Therefore, the constraint in Equation 3.1 renders the levels of factor x_i dependent, which makes the mixture experiment method different from the usual response surface or factorial experiments.

Table 3.4. Mixture Components and Volume Fraction Ranges

Components	ID	Minimum volume fraction (m^3)	Maximum volume fraction (m^3)
[A] Cement	x_1	0.13	0.155
[B] Water	x_2	0.155	0.164
[C] Coarse aggregates	x_3	0.407	0.43
[D] Fine aggregates	x_4	0.256	0.281
[E] HRWRA	x_5	0.003	0.004

Table 3.5. Mixture Components and Mass Fraction Ranges

Components	ID	Minimum mass fraction	Maximum mass fraction
[A] Cement (kg/m^3)	x_1	372	443
[B] Water (kg/m^3)	x_2	155	164
[C] Coarse aggregates (kg/m^3)	x_3	1066	1127
[D] Fine aggregates (kg/m^3)	x_4	671	736
[E] HRWRA (lit/m^3)	x_5	3.3	4.4

In general, the experimental region for a mixture of q components is a simplex with q vertices in q-1 dimensions. The coordinate system for the mixture space is a simplex coordinate system. Physical, theoretical or economical consideration often imposes additional constraints on the individual components. In this case, the feasible mixture region is no longer a simplex. The upper and lower bounds on the component properties are as follows:

$$0 \leq L_i \leq x_i \leq U_i \leq 1 \qquad i=1, 2, 3, \ldots, q \qquad [3.2]$$

where, L_i and U_i denote lower and upper bounds respectively. In cases where $q \geq 4$, lower and upper bounds make the experimental region more like irregular polyhedron. As such, a computer-based algorithm is required to develop a design for such a region. Most of computer-generated designs are based on the optimal design theory. Some optimal criterion focus on obtaining the accurate estimates of model parameters (D-optimality, A-optimality), while others focus on the accurate prediction of the model parameters in the design region (G-, V-, I-, and IV-optimality) (Smith, 2005; Myers and Montgomery, 2008).

In this research, both upper-bound and lower-bound constraints of concrete components are active along with the other constraints on the design space. This makes an irregular hyperpolytope in the feasible design space (Myers and Montgomery, 2008). Where prediction is important, the computer based IV-optimal design is recommended for generating experimental design points; it provides lower average prediction variance across the region of experimentation. The algorithm of IV-optimal design picks points that minimize the integral of the prediction variance across the design space. Since one of the primary objectives of this research is to produce accurate prediction of the responses throughout the design space, IV-(integrated variance) optimality is applied to generate the design space (Smith, 2005; Myers and Montgomery, 2008).

To simplify the calculation and analysis, the actual variable ranges are transformed to dimensionless coded variable with ranges of ±1.The variable x_1 to x_5 are codified using the following formula:

$$U_{Pseudocomponent}=(U_i-x_i)/(U-1) \qquad [3.3]$$

whereU_i is the upper-bound for the i^{th} component, x_i is the uncoded value, and U is the sum of upper-bounds. When using $U_{pseudocomponent}$ transformation, it should be noticed that the $U_{pseudocomponents}$ have effects that are opposite those of the real components (Smith, 2005).

According to Myers and Montgomery (2008), the properties of a good design can be grouped into a design and an analysis stages. Some properties can be integrated at the design stage (before any data are collected), but others cannot be checked and possibly adjusted after data are collected and analysis is performed. In the design stage, an appropriate experiment design depend on several criteria, such as generating a satisfactory distribution of information, being cost-effective, building an appropriate model, providing an estimate of repeatability, and being able to check the adequacy of the fitted model. Choosing a proper model that will adequately explain the data and will explore relationship between variables can lead the experimenter to achieve the "best" experimental design. The Scheffé canonical polynomial, which is used in this research, is the most commonly encountered mixture model reported in the literature. A second-order model is considered to be more appropriate over the first-order model as the literature indicates that interaction terms are mostly significant. Where optimization is considered to be important, it is better to use a second-order and higher-order model, which are commonly called "response surface models". The general form of a quadratic Scheffé polynomial is written as:

$$E(Y)=\sum_{i=1}^{q} \beta_i x_i+\sum_{i=1}^{q-1}\sum_{j=i+1}^{q} \beta_{ij} x_i x_j \qquad [3.4]$$

where, $x_i x_j$ is referred to as quadratic blending terms in the mixture experiments and coefficients β_{ij} are referred to as quadratic or nonlinear blending coefficients. Where $\beta_{ij} \neq 0$, it means blending between components (x_i and x_j) is synergistic (Smith, 2005). The number of terms in this model is the same as the number of components in the mixture, and the interpretation of such a model for a mixture is easier than other forms of polynomial.

3.6. Number of Mixtures

In the current research, the five-component quadratic Scheffé polynomial is used:

$$Y=b_1x_1+b_2x_2+b_3x_3+b_4x_4+b_5x_5+b_{12}x_1x_2+b_{13}x_1x_3+b_{14}x_1x_4+b_{15}x_1x_5$$
$$+b_{23}x_2x_3+b_{24}x_2x_4+b_{25}x_2x_5+b_{34}x_3x_4+b_{35}x_3x_5+b_{45}x_4x_5+e \qquad [3.5]$$

There are 15 coefficients in this model. Therefore, the design must have at least 15 distinct runs (mixes) to estimate coefficients. Also, in order to check the adequacy of the fitted model (lack of fit), two additional runs are added to the design. Finally, in order to test the statistical significance of the final coefficients, two runs are replicated; there is also one additional center point. In total, 20 mixtures are cast to adequately estimate the defined properties.

The commercially available software Stat-Ease Design Expert Ver. 8 software (2010)is used to design and analyze the experiments for the experimental design. The program uses the IV-optimal design to designate design points for fitting a quadratic polynomial. This means that the algorithm searches for the best available combinations of points satisfying the design region constraints and yielding the best prediction of responses in the design region.

The detailed proportion of mixtures study in volume and mass fraction are given in Tables 3.6 and 3.7, respectively. The run orders are randomized to reduce the effects of bias that may adversely affect the result of the experiments.

3.7. Mixing Procedure

All mixes are prepared in a concrete pan mixer with a nominal capacity of 0.1 m^3. Each mix is approximately 0.075 m^3 in volume, The following procedure is used in the preparation of all mixtures. Moisture content of both fine and coarse aggregates is measured according to ASTM C127 - 12 and ASTM C127- 12 standards. Depending on the moisture content of the aggregates and their absorptions, the amount of mixing water, coarse aggregates, and fine aggregates are adjusted to ensure that the amount of w/c ratio of the mix is accurate and consistent. Fine and coarse aggregates are first mixed for 30 seconds; and within the following 30 seconds cement is added with the adjusted mixing water. Afterward, HRWRA is added. Initial mixing takes place for 3 minutes. The mixing is then stopped for 3 minutes for absorption. Mixing is then resumed for another 3 minutes. Slump is measured after completion of mixing according to relevant ASTM procedure. The cylinders are roded and the prisms are vibrated on a vibration table in accordance with ASTM C31 / C31M - 12. The cylinders and prisms are covered with plastic sheets and are left in the casting room at 20 C° for 24 hours. The samples are stripped and kept inside the curing room with a humidity ratio of 100 % and a temperature of 23 ± 2 C° until testing.

3.8. Test Procedures

The compressive strength is determined using 100 mm × 200 mm (4" × 8") cylinders at 3- 7- 28- 56- and 91-day. Three cylinders are tested at each age for each concrete mixture. The compressive strength tests are carried out in accordance with ASTM C39 / C39M - 12. Before testing, the cylinders are capped according to ASTM C617 / C617M - 11 using melted sulfur mortar.

The modulus of rupture (flexural strength) is determined using a simple beam with third-point loading in accordance with the ASTM C78 / C78M - 10 standard. The beam size is 100 mm × 100 mm × 400 mm (4" × 4" × 16"). Flexural strength is measured at 3- 7- 28- and 56-day.

The modulus of elasticity is determined in accordance with ASTM C469 / C469M - 10 at 3- 7- 28- and 56-day. The tests are carried out using 100 mm × 200 mm (4" × 8") cylinders. The applied load related to a longitudinal strain of $50x10^{-6}$, and longitudinal strain related to 40 % of the ultimate load is used to calculate the modulus of elasticity.

Table 3.6. Mixture Experiment Design in Terms of Volume Fraction of Components

Standard Order	Design ID	Run Order	Type	A Cement	B Water	C Coarse Agg.	D Fine Agg.	E HRWRA
6	6	1	Vertex	0.140	0.164	0.415	0.277	0.004
5	5	2	Vertex	0.155	0.155	0.430	0.256	0.004
18	15	3	Edge	0.155	0.155	0.420	0.267	0.003
11	0	4	Center	0.144	0.161	0.421	0.271	0.003
4	4	5	Edge	0.145	0.164	0.430	0.257	0.004
8	7	6	Interior	0.153	0.162	0.419	0.262	0.004
19	16	7	Edge	0.155	0.155	0.425	0.262	0.003
12	0	8	Center	0.144	0.161	0.421	0.271	0.003
15	12	9	Plane	0.137	0.164	0.427	0.270	0.003
7	7	10	Interior	0.153	0.162	0.419	0.262	0.004
14	11	11	Plane	0.149	0.159	0.430	0.259	0.003
13	10	12	Plane	0.155	0.164	0.408	0.269	0.003
10	9	13	Plane	0.130	0.162	0.424	0.281	0.003
3	3	14	Plane	0.154	0.158	0.411	0.272	0.004
2	2	15	Plane	0.134	0.158	0.430	0.275	0.004
9	8	16	Plane	0.144	0.155	0.420	0.277	0.004
20	17	17	Vertex	0.155	0.164	0.423	0.256	0.003
17	14	18	Edge	0.146	0.160	0.415	0.277	0.003
16	13	19	Unknown	0.132	0.156	0.430	0.279	0.004
1	1	20	Plane	0.144	0.164	0.425	0.264	0.004

3.9. Results and Statistical Analysis

3.9.1. Measured Responses

The average value of all performance results, including slump, compressive strength (3- 7- 28- 56- and 91-day), modulus of rupture (3- 7- 28- and 56-day), and modulus of elasticity (3- 7- 28- and 56-day) for each batch are given in Table 3.8. In addition, the test results of all samples for measured responses are presented in Tables C-1 and C-2 in Appendix C. A mathematical prediction model is fitted for each measured response using the least-squares method and ANOVA. The model is validated by examining the residuals for trends and outliers. The appropriate transformation is applied if needed, and finally, the results are interpreted graphically using contour and trace plots.

Table 3.7. Mixture Proportions for Mixture Experiments (per cubic meter of concrete)

Design ID	Run Order	Cement (kg/m^3)	Water (kg/m^3)	Coarse Agg. (kg/m^3)	Fine Agg. (kg/m^3)	HRWRA ($lit./m^3$)	w/c[1]	CA/FA[2]
6	1	401	164	1088	725	4.40	0.41	1.50
5	2	444	155	1127	670	4.40	0.35	1.68
15	3	444	155	1099	701	2.81	0.35	1.57
0	4	411	161	1104	711	3.62	0.39	1.55
4	5	415	164	1127	674	4.40	0.39	1.67
7	6	438	162	1099	686	4.20	0.37	1.60
16	7	444	155	1114	686	2.81	0.35	1.62
0	8	411	161	1104	711	3.62	0.39	1.55
12	9	391	164	1118	708	2.83	0.42	1.58
7	10	438	162	1099	686	4.20	0.37	1.60
11	11	426	159	1127	680	3.18	0.37	1.66
10	12	444	164	1070	705	3.59	0.37	1.52
9	13	371	162	1111	736	3.63	0.44	1.51
3	14	441	158	1078	713	4.40	0.36	1.51
2	15	382	158	1127	719	4.40	0.41	1.57
8	16	412	155	1101	725	3.92	0.38	1.52
17	17	444	164	1108	725	2.81	0.37	1.53
14	18	416	160	1088	725	2.81	0.38	1.50
13	19	378	156	1127	725	3.96	0.41	1.55
1	20	412	164	1112	725	4.40	0.40	1.53

[1]w/c water per cement ratio

[2]CA/FA coarse-to- fine aggregate ratio

Table 3.8. Test Results

		Compressive Strength					Modulus of Rupture				Modulus of Elasticity			
Run Order	Slump (mm)	3-day (MPa)	7-day (MPa)	28-day (MPa)	56-day (MPa)	91-day (MPa)	3-day (MPa)	7-day (MPa)	28-day (MPa)	56-day (MPa)	3-day (GPa)	7-day (GPa)	28-day (GPa)	56-day (GPa)
1	145	31.06	40.78	54.95	63.50	63.80	3.86	4.72	6.28	6.79	29.3	30.6	33.1	33.6
2	75	38.42	48.25	64.27	72.57	75.06	4.92	5.83	7.39	7.67	31.1	33.7	35.5	36.3
3	24	36.81	46.44	59.77	62.21	65.21	4.59	6.02	7.40	7.66	31.7	32.3	34.7	36.1
4	54	31.37	40.36	55.83	58.15	61.44	4.09	4.95	6.45	7.27	29.0	30.4	32.6	34.2
5	140	32.73	40.50	57.55	61.56	62.49	3.83	5.04	6.33	6.56	30.8	32.6	33.2	34.2
6	72	35.25	43.61	62.28	68.19	67.48	4.61	5.49	6.86	7.56	28.8	33.0	34.3	34.6
7	30	36.61	46.10	58.22	64.85	64.70	5.02	5.62	7.24	7.32	28.9	33.1	35.3	35.2
8	48	33.94	42.37	55.93	60.69	66.34	4.29	5.13	6.94	7.18	29.7	33.2	33.2	34.9
9	87	30.49	39.37	53.19	58.53	63.26	3.92	4.58	6.50	6.90	27.9	29.7	33.5	34.0
10	140	35.10	41.58	59.47	65.56	68.08	4.30	5.17	6.64	6.99	28.3	31.2	34.6	34.0
11	50	34.93	46.17	59.54	62.56	65.22	4.13	5.24	6.83	7.06	29.7	32.7	34.8	35.9
12	73	34.06	43.65	60.00	61.24	65.04	4.58	5.61	6.69	7.47	29.2	30.9	34.3	34.7
13	150	25.85	34.27	49.47	51.86	57.23	3.50	4.30	5.80	6.27	24.2	28.7	31.9	32.1
14	97	36.22	46.49	62.06	67.10	67.94	4.34	5.61	6.87	7.32	29.9	33.9	35.1	36.0
15	100	31.78	38.30	56.17	59.57	59.98	4.03	5.04	6.53	6.81	28.7	32.4	33.7	35.5
16	70	34.84	45.32	59.90	65.82	70.96	4.52	5.03	6.74	7.26	28.9	32.5	34.2	34.9
17	23	37.38	45.08	59.14	60.69	68.96	4.89	5.12	6.80	7.36	30.2	31.4	34.6	35.5
18	27	34.33	45.68	59.84	63.71	67.97	4.74	5.37	7.11	7.32	29.8	31.7	34.6	34.8
19	75	30.74	37.30	57.85	61.08	63.73	4.19	5.75	7.03	7.03	31.8	32.1	34.0	35.6
20	135	33.30	43.09	58.97	62.40	64.81	4.13	4.90	6.70	7.01	28.5	31.8	33.6	34.2
Max.	150	38.42	48.25	64.27	72.57	75.06	5.02	6.02	7.4	7.67	31.8	33.9	35.5	36.3
Min.	23	25.85	34.27	49.47	51.86	57.23	3.5	4.3	5.8	6.27	24.2	28.7	31.9	32.1
AVG.	80.75	33.76	42.73	58.22	62.59	65.48	4.32	5.23	6.76	7.14	29.3	31.9	34	34.8

3.9.2. Model Identification and Verification for 28-day Compressive Strength

In this section a detailed description of model identification and validation is described for the 28-day compressive strength response. The models for other responses are identified and validated in the same way.

The first step in the analysis of the data generated from experiments is to select the appropriate model. This is achieved by constructing models that describe each response over the applicable ranges. In the current research, although the IV-optimal design permits an estimation of a quadratic model, a linear model is examined as it may provide a better description of the data. To construct an appropriate model, statistical procedures such as analysis of variance (ANOVA) and the least squares technique are often used to develop the multivariate relationship linking measured characteristics and performance levels achieved. Once the model has been fitted, it is important to verify the adequacy of the chosen model quantitatively and graphically. In addition, the responses may be subjected to a power transformation (e.g. square root, log, etc.) to improve the goodness of fitted model and to meet the assumption of regression. As is explained, ANOVA is used to assess the appropriate type of model.

The sequential model sum of squares for the 28-day compressive strength is shown in Table 3.9. This table shows the significance of linear, quadratic, and higher order models for the 28-day compressive strength using a sequential F-test and p-value. In general, the significance of the model is judged by determining if the probability that the theoretical value is greater or less than the F-statistic calculated from the data. The probability decreases if the value of the calculated F-statistic increases.

In other words, the significance of linear terms in the model is a test of the hypothesis that there is no linear relationship among factors in the mixture. Expressed formally, the hypotheses to be tested are

$$\begin{aligned} H_0&: \quad \beta_1 = \beta_2 = \beta_3 = \cdots = 0 \\ H_1&: \quad \text{At least one equality is false} \end{aligned} \qquad [3.6]$$

Also, the p-value is a measure of how likely the null hypothesis can be rejected. If p-value is less than 0.05 or less than other level of significance sets with the experimenter, then the terms are considered significant and their inclusion improves the model (Myers & Montgomery, 2008).

The linear terms in Table 3.9 have F_{value}= 13.33 with a P-value of $P < 0.0001$, so H_0 is rejected; therefore, the linear terms should be included in the model. The row with source "quadratic" in the sequential F-tests table indicates that the contribution of the quadratic terms to the model is not significant. Since the F_{value}=1.68 is so small and the "Prob > F" of 0.2929 exceeds 0.05, the quadratic terms should not be included in the model.

Table 3.9. Sequential Model Sum of Squares for 28-day Compressive Strength

Source	Sum of Squares	Degree of Freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	67791.37	1	67791.37			
Linear vs. Mean	165.37	4	41.34	13.33	< 0.0001	Suggested
Quadratic vs. Linear	35.87	10	3.58	1.68	0.2929	
Sp Cubic vs. Quadratic	6.66	3	2.22	1.12	0.5027	Aliased
Residual	3.95	2	1.97			

The second step is to perform the lack of fit test using the ANOVA. The lack of fit test compares the residual error to the pure error from the replications. The lack of fit involves determining the part of residual sum of squares that can be predicted by including additional terms of the predictor variables in the model (e.g. higher-order polynomial or interaction terms) and the part of residual sum of squares that cannot be predicted by any additional terms (i.e. the sum of squares for pure error). To carry out this test, the residual sum of squares is partitioned into lack-of-fit and pure-error from the replicates. The model has significant lack of fit if residual error significantly exceeds pure error. Mean squares and F statistics are calculated, and the "Prob > F" is determined. If "Prob > F" is less than 0.05, then the lack of fit is significant, which is not desirable. Consequently, another model may be more appropriate (Myer and Montgomery, 2008).

For the 28-day compressive strength, the lack of fit test of the linear model gives "Prob > F" equal to 0.4388 (Table 3.10), which is non-significant. Hence, the linear mixture model is adequate.

Table 3.10. Lack of Fit Tests for 28-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Linear	42.53	13	3.27	1.65	0.4388	Suggested
Quadratic	6.66	3	2.22	1.12	0.5027	
Special Cubic	0	0				Aliased
Pure Error	3.95	2	1.97			

The resulting linear model for the 28-day compressive strength fitted by standard linear regression technique (least squares) in terms of U-Pseudo components is shown in Table 3.11.

Table 3.11. Prediction Model for 28-day Compressive Strength

Prediction model equations for 28-day compressive strength(MPa) In the form, $E(Y)= \sum_{i=1}^{q} \beta_i x_i + \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} \beta_{ij} x_i x_j$					
Components	A	B	C	D	E
Coefficient	+ 50.39	+ 71.25	+ 60.63	+ 61.33	- 2.81

The coefficient of the individual variable in each equation gives a measure of variable's effect on the predicted response. For instance, if a variable has a large coefficient, then even a marginal increment will give a significant change on the response. By solving the equation, an individual property can be minimized and maximized, leading to an optimum combination of components.

Four summary statistics can be calculated to verify the model adequacy. Firstly, the R^2 indicates how well the model fits the data. The R^2 removes the proportion of total variability explored by the model. Nonetheless, it cannot be relied on because it always increases as factors are added to the model, even if these factors are not significant. Secondly, "Adjusted R^2"adjusts for the "size" of the model. It is a measure of the amount of variation about the mean explained by the model. The Adjusted R^2 can actually plateau if non-significant terms are added to a model. Thirdly, prediction error sum of square (PRESS), is the measures of how well the model fits each point in the design. To calculate PRESS, a model is used to estimate each point using all of the design points except the one being estimated. A model with small PRESS indicates that the model is likely to be a good predictor. Fourthly, the predicted R^2 (R^2_{pred}) statistic indicates how well the model predicts responses for new observation. Predicted R^2 decreases when there are too many insignificant terms in the model. A good model has a large predicted R^2 and a low PRESS.

Table 3.12. Model Summary Statistics for 28-day Compressive Strength

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	1.76	0.78	0.72	0.60	84.42	Suggested
Quadratic	1.45	0.95	0.81	-0.49	315.70	
Special Cubic	1.40	0.98	0.82		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

Table 3.12shows the summary statistics for the compressive strength at 28-day. The results show that $R^2_{adj} = 0.78$ and $R^2_{pred} = 0.6$ are in reasonable agreement; the model with the $R^2_{pred} = 0.6$ has a good chance of making reasonable prediction.

Validation of the basic assumption of the ANOVA and model adequacy can be investigated by the examination of residuals. The residuals are the deviation of observed data from the predicted value. The residuals, which are the estimation of the error terms in the model, are assumed to be structureless and to be normally distributed with a mean zero and a constant standard deviation. There are three model assumptions checks: checks for the normality assumption, checks for the homogeneous variance assumption, and checks for independence assumption. Figure 3.3 displays a Design-Expert normal probability plot of the studentized residuals. This plot resembles a straight line, which means that the underlying error distribution is normal, so the first assumption of ANOVA is satisfied.

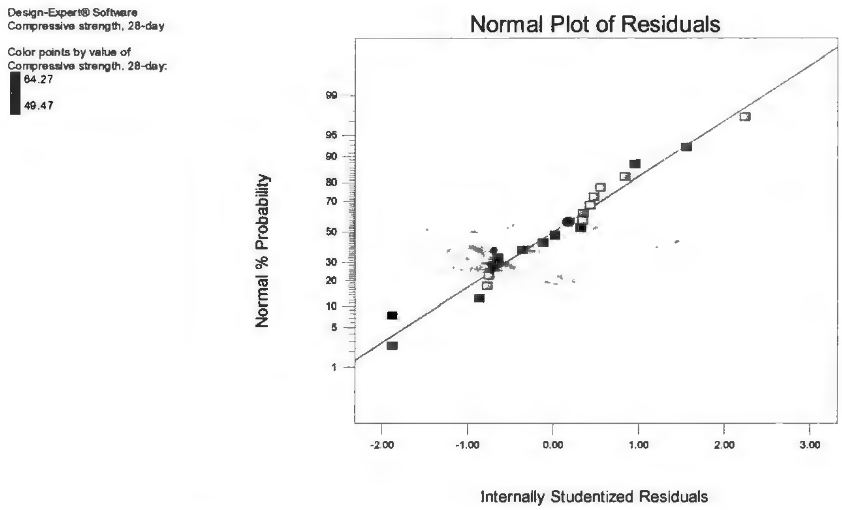

Figure 3.3.Normal Probability Plot of Residuals

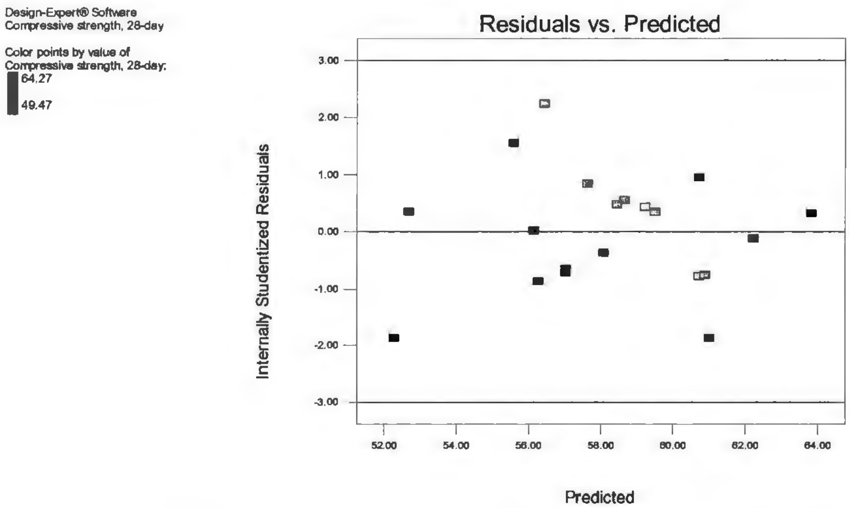

Figure 3.4. Plot of Residuals vs. Predicted

Figure 3.4 displays a Design-Expert plot of studentized residuals vs. predicted values. The plot shows that the residuals fall randomly within a horizontal band with no pattern, which means that the residuals appear to be independent of the size of the fitted value and have constant variance. This indicates that the second ANOVA assumption is satisfied.

Figure 3.5 illustrates a Design-Expert plot of studentized residuals vs. run order. This plot is used to detect the correlation between the residuals that may accrue as a result of no proper randomization of the experiments. There is no tendency to have positive or negative residuals in the plot. This implies that the independence on the error terms has not been violated. Overall, since all the assumptions of an adequate model are valid, one deduce that the model provides an adequate fit to the observed data.

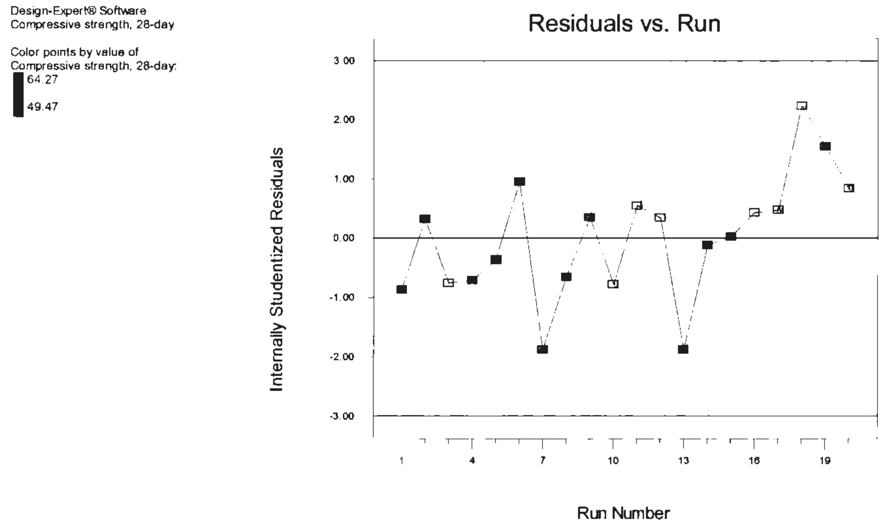

Figure 3.5. Plot of Residuals vs. Run

3.10. Model Development for Other Concrete Properties

Using the same procedure of model identification for the 28-day compressive strength, the following prediction models are developed for to the other concrete properties. The analyses for these properties are performed in similar manner. The Sequential model sum of squares, the lack of fit tests and the summary statistics tables of these models are presented in TablesD.1 to D.52in Appendix D.

The details of developed models for 3- 7- 56- and 91-day compressive strength, 3- 7- 28- and 56-day flexural strength (modulus of rupture), and 3- 7-28- and 56-day modulus of elasticity are shown in Table 3.13. The goodness of fit are also summarized in Table 3.14.

Table 3.13. Prediction Models for Measured Properties of Concrete

Summary of prediction model equations (in the form, $E(Y)= \sum_{i=1}^{q} \beta_i x_i + \sum_{i=1}^{q-1} \sum_{j=i+1}^{q} \beta_{ij} x_i x_j$)

Description of variable [1] (x_i)	Equation constants (β_i and β_{ij})											
	Ln (Slump) (mm)	Compressive strength (MPa)				Modulus of rupture (MPa)				Modulus of elasticity (Gpa)		
		3-day	7-day	56-day	91-day	3-day	7-day	28-day	56-day	7-day	28-day	56-day
A	5.43	25.44	32.6	54.16	50.06	3.23	4.12	6.92	6.27	30.18	31.64	33.04
B	2.89	43.42	54.35	80.96	99.12	5.77	7.49	8.82	8.39	38.84	38.29	40.54
C	4.77	34.21	44.74	65.53	61.72	4.42	5.39	6.55	7.44	31.43	34.00	33.91
D	4.81	36.63	44.5	66.61	67.27	4.37	5.25	6.70	7.14	32.79	34.45	34.96
E	-22.3	29.8	56.98	48.17	36.99	9.09	3.96	10.34	9.02	5.29	35.23	37.44
AC	---	---	---	---	34.83	---	---	---	---	---	---	---
BE	---	---	---	---	106443	---	---	---	---	---	---	---

[1] A: cement, B: water, C: coarse aggregate, D: fine aggregate, E: HRWRA

Linear models are fit to all responses except the slump and the 91-day compressive strength. The quadratic model is adequate for the 91-day compressive strength, and the natural logarithm transform is applied to model the slump. Furthermore, no model is fit to the 3-day modulus of elasticity. The results for this response only present the overall mean.

Table 3.14 gives information on the summary statistics of all developed models. According to the summary statists, R^2_{pred} is moderately low for some of the models. This means chance of good prediction might be low.

Table 3.14. Summary Statistics of goodness of fit of developed Models

Performance Criteria	R^2	R^2_{Adj}	R^2_{pred}	PRESS
Slump	0.82	0.77	0.67	2.43
3-day compressive strength	0.88	0.85	0.79	33.51
7-day compressive strength	0.80	0.75	0.65	86.58
56-day compressive strength	0.73	0.66	0.49	176.63
91-day compressive strength	0.80	0.71	0.60	116.90
3-day modulus of rupture	0.74	0.67	0.51	1.54
7-day modulus of rupture	0.79	0.73	0.60	1.37
28-day modulus of rupture	0.74	0.68	0.57	1.10
56-day modulus of rupture	0.74	0.66	0.52	1.00
3-day modulus of elasticity[1]	-	-	-	-
7-day modulus of elasticity	0.66	0.57	0.48	14.32
28-day modulus of elasticity	0.76	0.70	0.61	6.53
56-day modulus of elasticity	0.72	0.64	0.48	8.45

[1]No model is fit to the 3-day modulus of elasticity

CHAPTER 4

DISCUSSION

4.1. Introduction

In the previous chapter, the statistical mixture design procedure was adopted to design the concrete mix proportions and to establish the prediction equations. In this chapter, the effects of the mixture components are interpreted using trace plots and contour plots. Moreover, the graphical and numerical optimization procedures are described in detail; the optimum binder combinations are selected using both optimization procedures. Finally, three concrete mixtures that are selected using the prediction models are cast to verify the adequacy of the models in predicting the performance criteria.

4.2. Graphical Interpretation Using Trace Plots

Trace plot has been widely used in the experimental mixture design to assess the effects of mixture components on the measured responses. It is always useful to determine the number of components in the model by removing the less effective components. In general, trace plot can be drawn in the Cox direction introduced by Cox (1971), which is an imaginary line projected from the reference mixture (usually centroid) to the vertex (Smith, 2005). It reveals how the response changes with the variation of each component from its low to high setting in the design region, while keeping all others in the same relative ratio at a specified reference mixture, here the centriod. The horizontal and near horizontal trace for a component in a trace plot usually suggests this component has no effect on the results. Conversely, the effect of a component with a trace that is clearly not horizontal could be significant. The above interpretation all relay on the variance of the effect. The trace plots in the following sections show how the estimated responses are sensitive to the changes in the mixture proportions. As explained in the chapter 3, one must be careful in the interpretation of the coefficients of the fitted model where making inferences about the fitted surface in the original real components or in the U-pseudo unit because high and low levels of real components are inverted by U-pseudo coding. In other words, a negative slope in the trace plot means a positive effect and a positive slope means a negative effect. The steeper the slope the stronger the effect.

4.2.1. Slump

Figure 4.1 shows the trace plot of the slump. As expected, HRWRA and water content have positive effect on the slump. However, the most effective factor in increasing slump is HRWRA. An increase in cement content appears to reduce the slump. However, this apparent reduction may not be significant when compared to the effect of HRWRA and water, and compared to the error in the experiment. Also, the inclusion of silica fume with an extremely fine particles in this type of blended cement may slightly reduce workability of the mixtures. The coarse and fine aggregates have a negligible effect on variation of the slump.

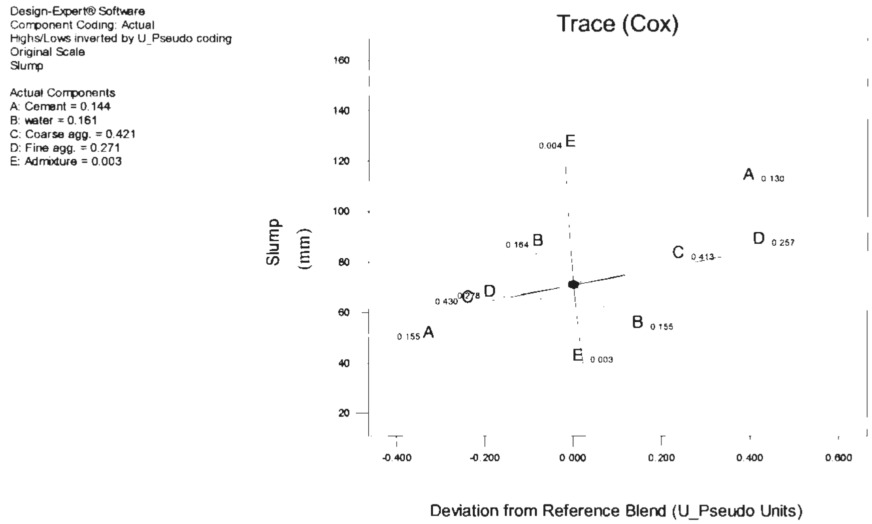

Figure 4.1. Trace Plot of the Slump

4.2.2. Compressive Strength

Figures 4.2 through 4.6 show the trace plots of the compressive strength at 3- 7- 28- 56- and 91-day. As expected, increasing the amount of cement content increases the compressive strength at all ages, while increasing water content decreases the compressive strength. Compared to the other components, coarse and fine aggregates have moderate effects on the compressive strength. Increasing the HRWRA yields higher compressive strength at all ages except 7-day.

Since the models for 3- 7- 28- and 56-day are linear, the trace plots for these responses are linear. The developed model for 91-day compressive strength is quadratic and the parabolic nature of traces for this response (Figure 4.6) indicates the nonlinear relationship between components. It shows that the estimated response is quite sensitive to changes in the mixture proportions.

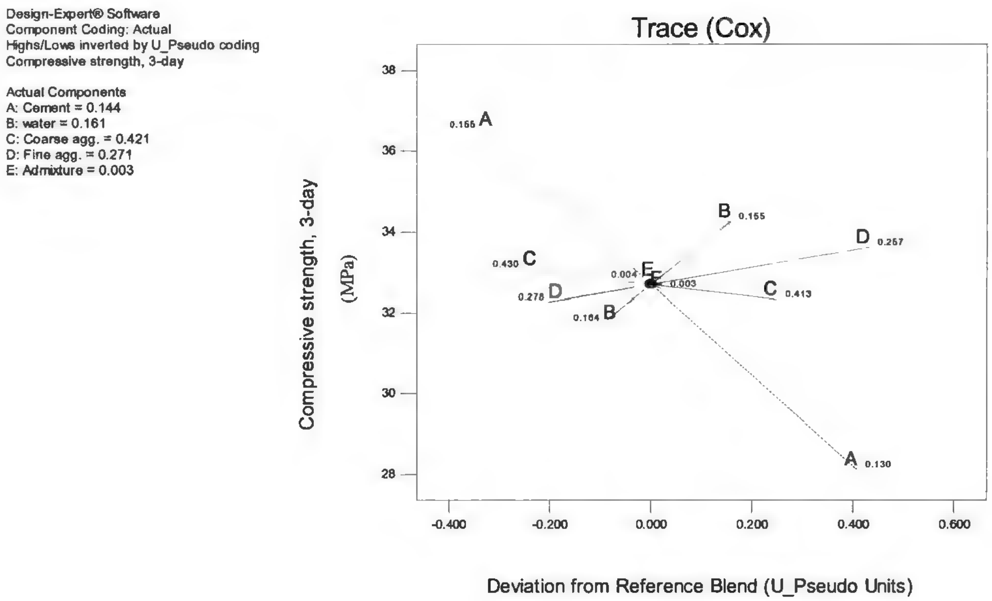

Figure 4.2. Trace Plot of 3-day the Compressive Strength

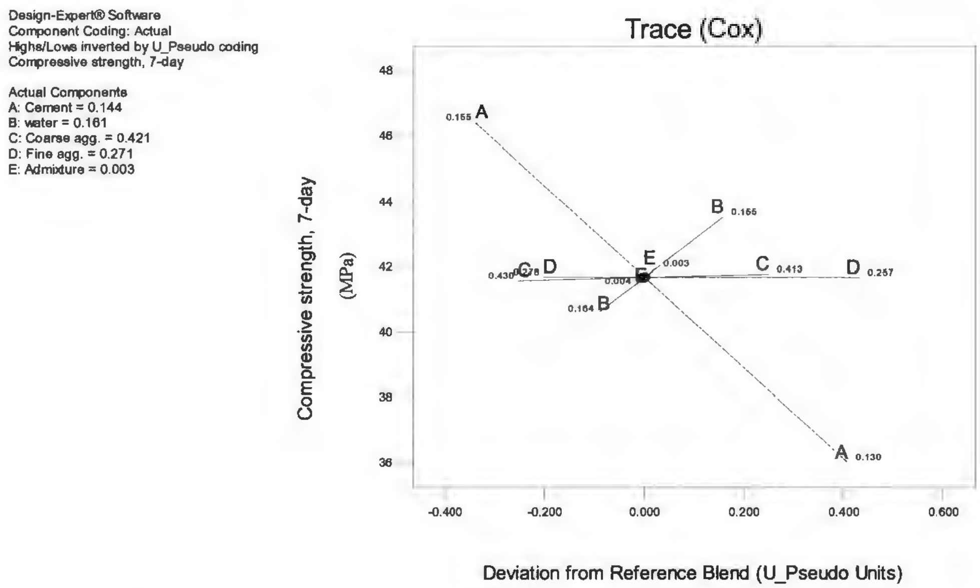

Figure 4.3. Trace Plot of the 7-day Compressive Strength

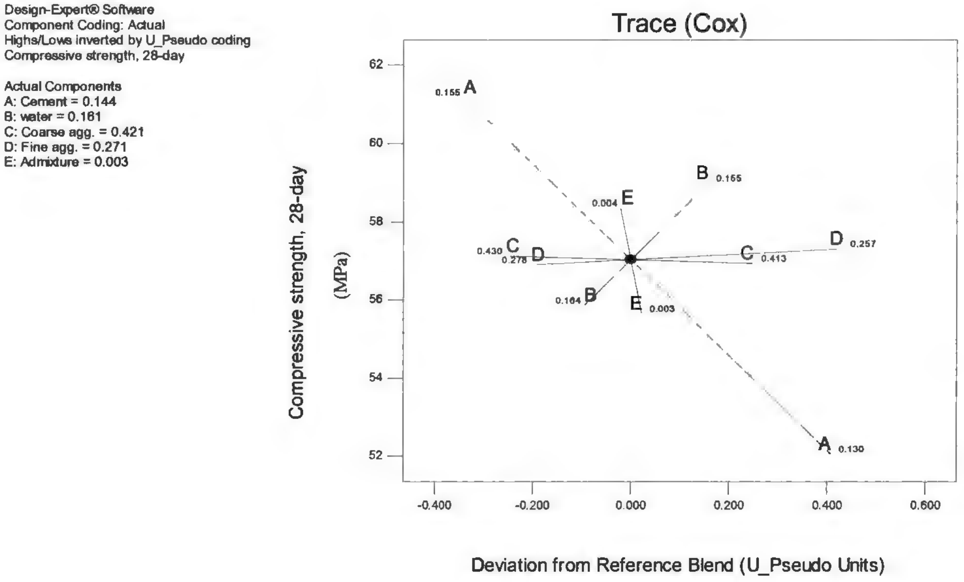

Figure 4.4. Trace Plot of the 28-day Compressive Strength

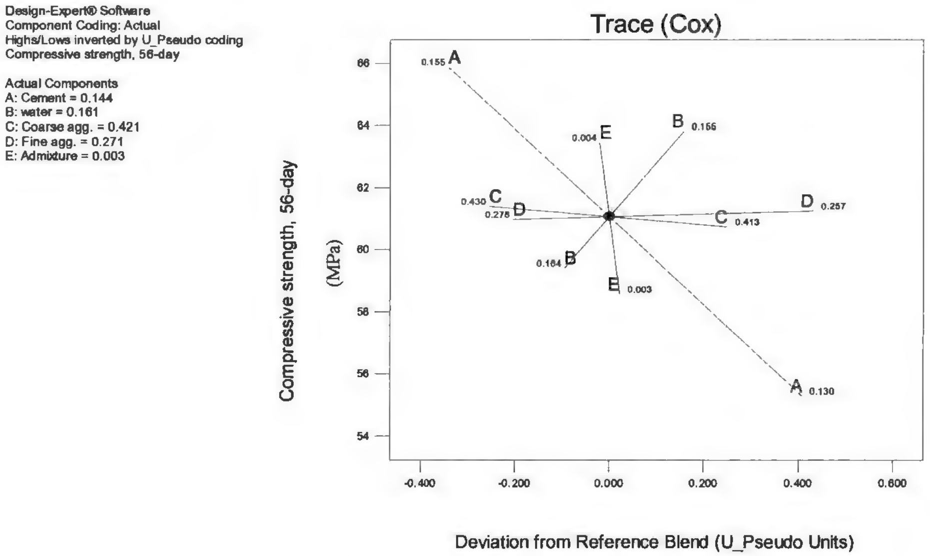

Figure 4.5. Trace Plot of the 56-day Compressive Strength

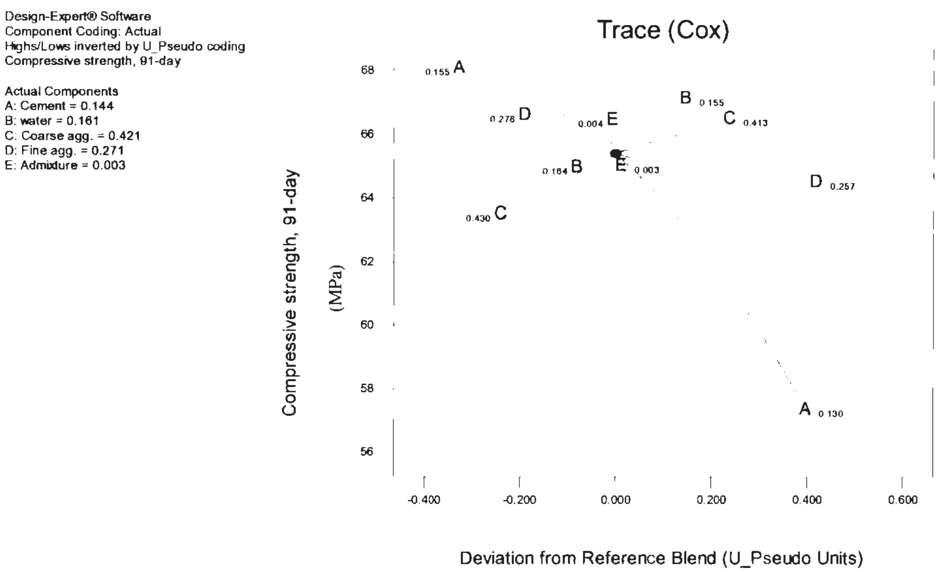

Figure 4.6. Trace Plot of the 91-day Compressive Strength

4.2.3. Flexural Strength (Modulus of Rupture)

Figures 4.7 through 4.10 show the trace plots of the modulus of rupture at 3- 7- 28- and 56-day. The cement and water content variation display similar effect for both the flexural strength (modulus of rupture) and the compressive strength. Increasing the cement content significantly increases the modulus of rupture. In general, the increasing water content has a negative effect on modulus of rupture. Again, changing in the coarse and fine aggregates content have negligible effects on the flexural strength, with the exception of28-day modulus of rupture, which demonstrates a pronounced positive effect of coarse and fine aggregates. Unlike compressive strength, HRWRA shows negative effect on modulus of rupture at all ages except 7-day. This effect is not significant, compared to the other components' effect.

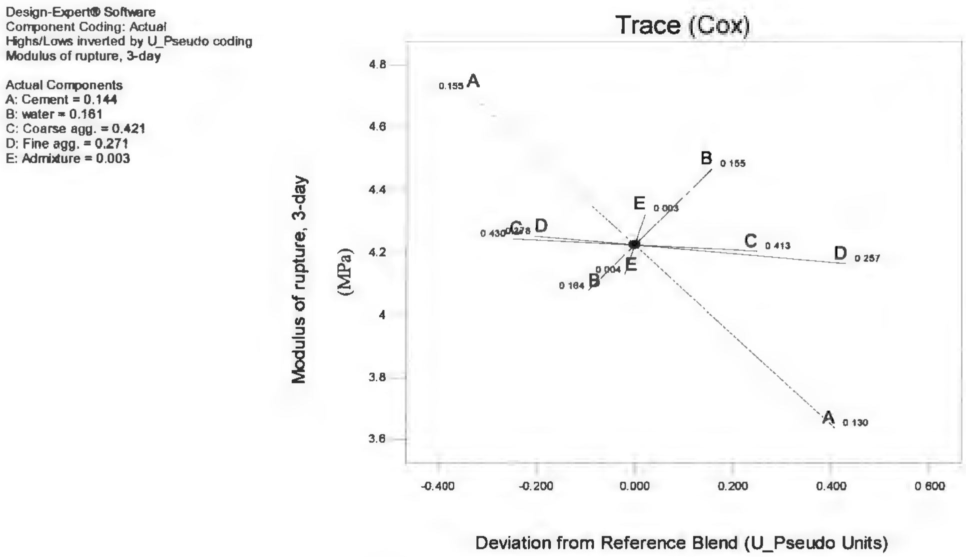

Figure 4.7. Trace Plot of the 3-day Modulus of Rupture

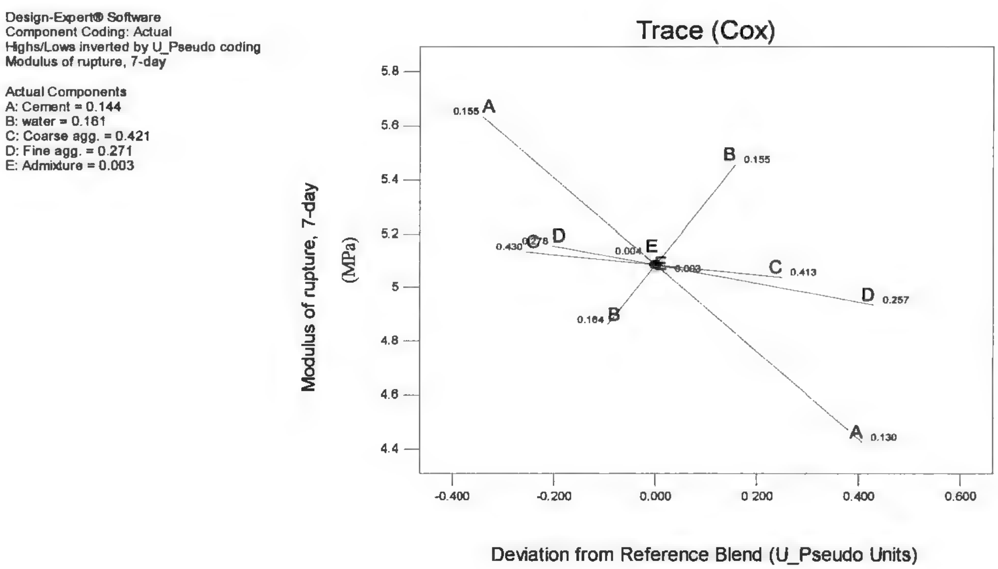

Figure 4.8. Trace Plot of the 7-day Modulus of Rupture

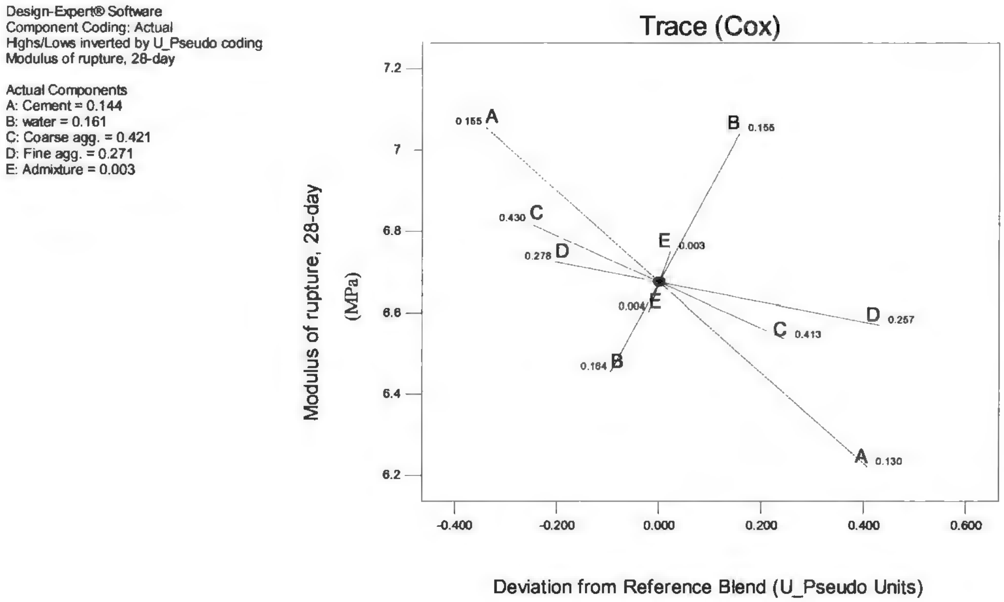

Figure 4.9. Trace Plot of the 28-day Modulus of Rupture

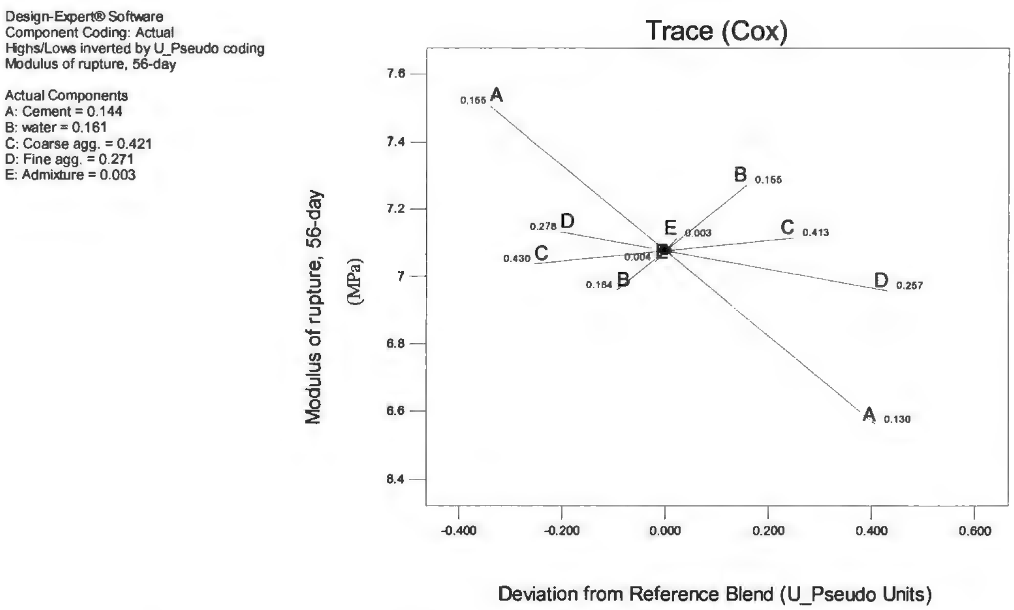

Figure 4.10. Trace Plot of the 56-day Modulus of Rupture

4.2.4. Modulus of Elasticity

Figures 4.11 through 4.13 show the trace plots of the modulus of elasticity at 7- 28- and 56-day. The results of 3-day modulus of elasticity cannot be statistically interpreted, and no model can be derived from the results. It is not possible to draw trace plot for this response. Increasing coarse aggregates content has a positive effect on modulus of elasticity at all ages. The positive effect of cement content and negative effect of water content on modulus of elasticity are similar to the compressive strength and the flexural strength at all ages. It is evident that increasing fine aggregates content has negligible effect on the modulus of elasticity at all ages.

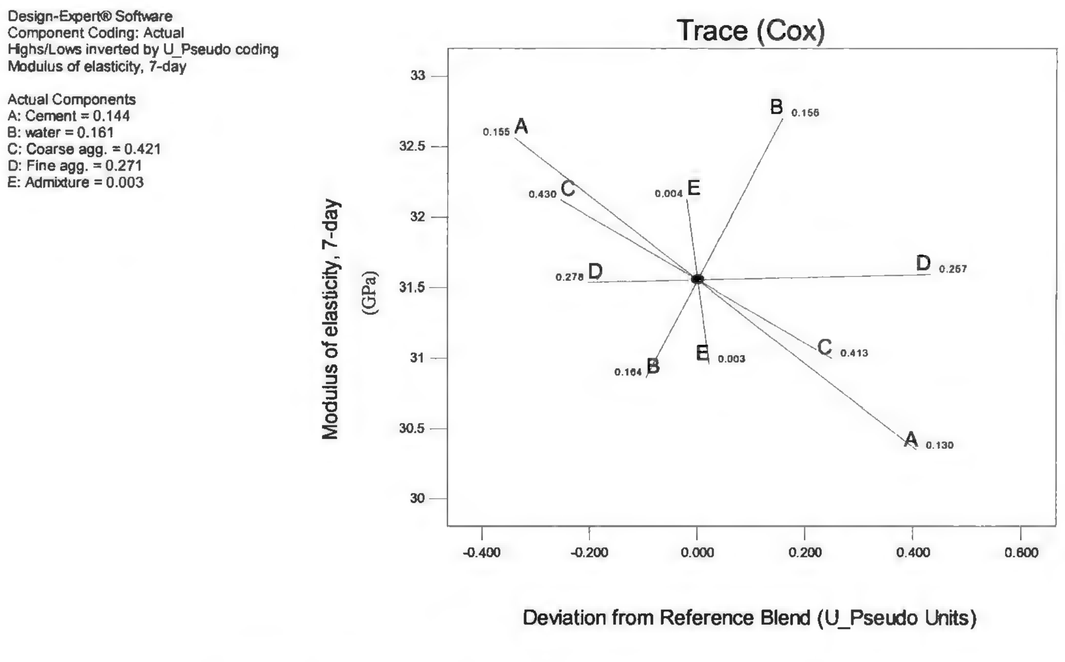

Figure 4.11. Trace Plot of the 7-day Modulus of Elasticity

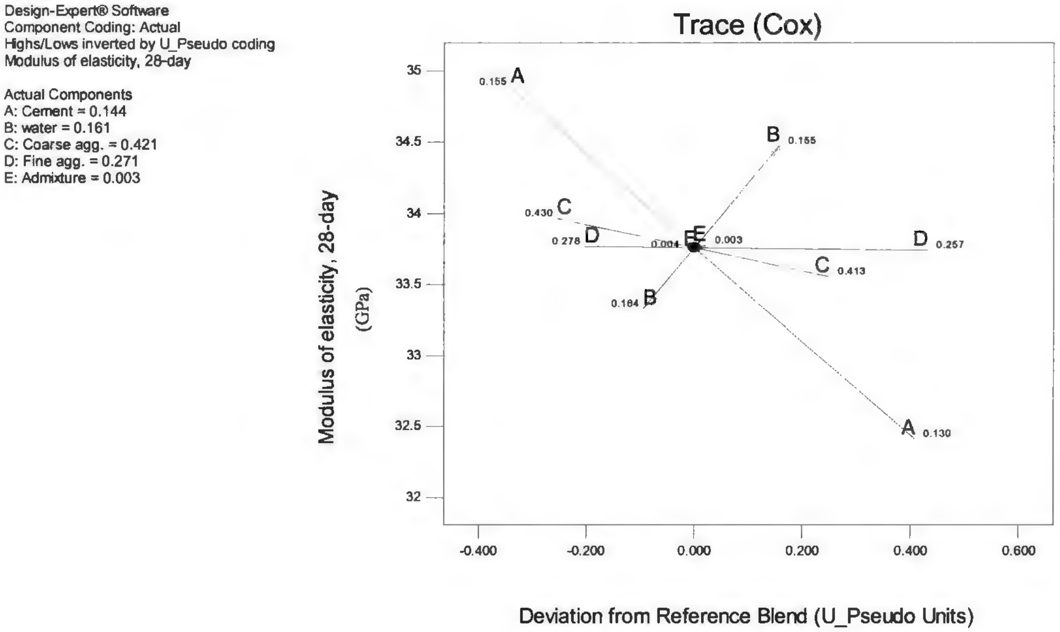

Figure 4.12. Trace Plot of the 28-day Modulus of Elasticity

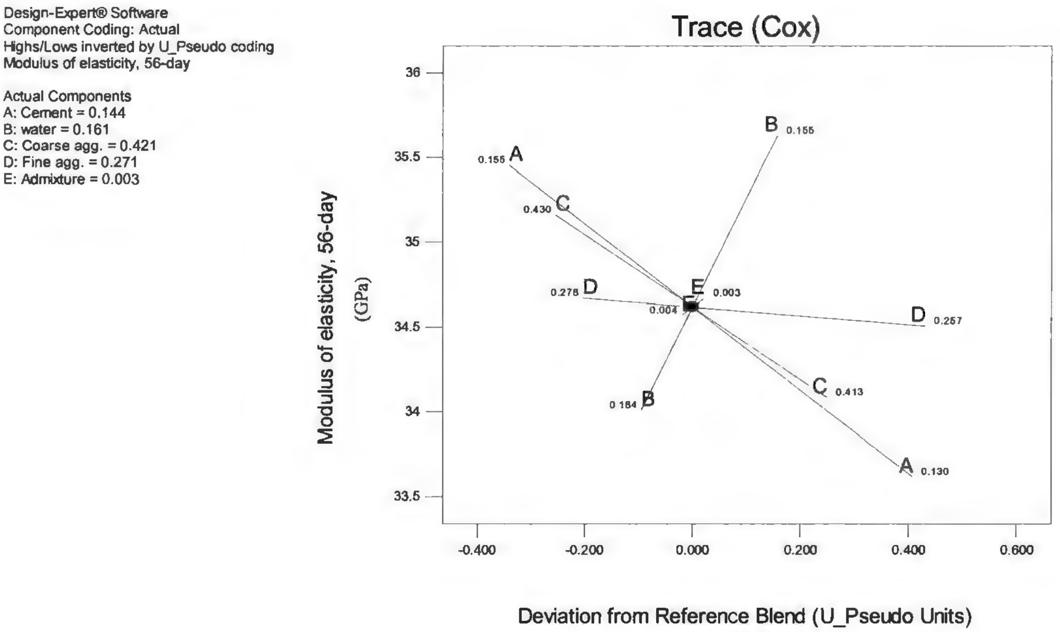

Figure 4.13. Trace Plot of the 56-day Modulus of Elasticity

4.3. Optimization Process

4.3.1. Graphical Optimization

The most common graphical approach for single-response optimization is using trilinear contour plots. Contour plots mostly are used to identify conditions that provide the maximum or the minimum of the responses. In a contour plot, one can look at only three components at a time, it is better to first examine trace plots for checking the most effective components, and leave the least effective components out of the ternary plot. Figure 4.14 is a contour plot of the 28-day compressive strength for water, cement and HRWRA, with all the other components fixed at selected values. The values are presented in terms of volume fraction that can be converted to weight using the specific gravity of components. According to this plot, the predicted 28-day compressive strength is 57.7 MPa where cement content is 420 kg/m^3, water content and HRWRA are154 kg/m^3 and 3.3lit/m^3, respectively. In addition, coarse and fine aggregates content are fixed at 1127 kg/m^3 and 671 kg/m^3, respectively.

The graphical approach for multiple-responses is using overlaid contour plots. This plot works well up to three responses but more than that need to check different contour plots. However, statistical software like Design-Expert has the capability of graying out the undesirable responses which makes it easier to interpret the results.

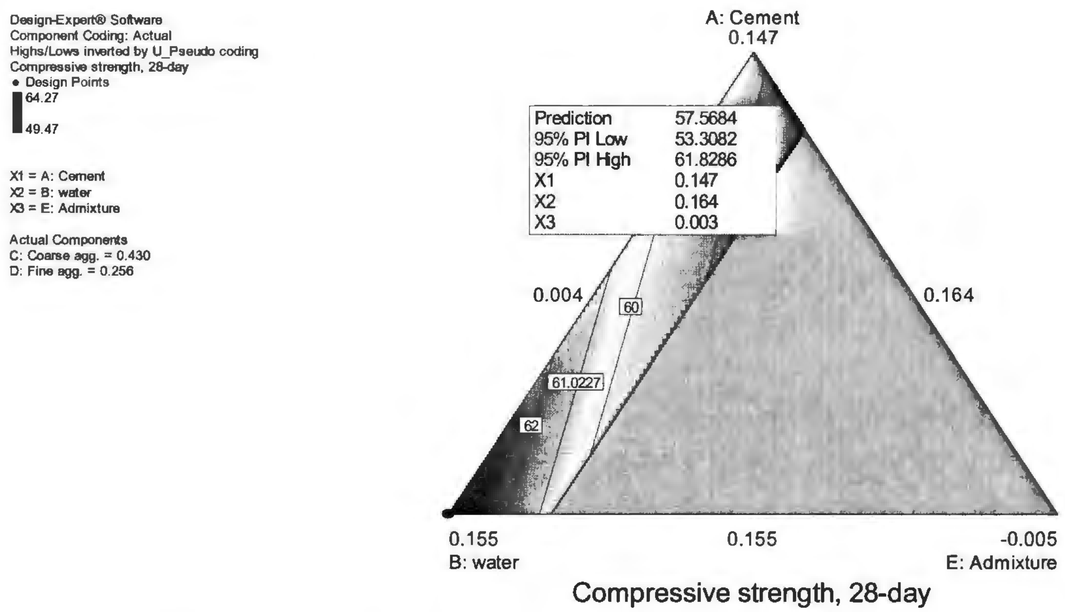

Figure 4.14. Contour Plot of the 28-day Compressive Strength in Water, Cement, and HRWRA

Table 4.1 shows the selected ranges of the responses and the predicted values using the developed models and the overlay contour plot (Figure 4.15). The results of verification tests based on this prediction are given in Table 4.7 later in this chapter.

Table 4.1.Defined Ranges and Predicted Values by Overlay Contour Plot

Responses	Ranges	Predicted values using overlay plot
Slump (mm)	55-100	85
Compressive strength 3-day(MPa)	29-38	33.88
28-day Compressive strength (MPa)	53-65	57.56
56-day Compressive strength (MPa)	56-65	61.55
28-day Flexural strength at (MPa)	6-7.3	6.58
28-day Modulus of elasticity (GPa)	32-34	33.8

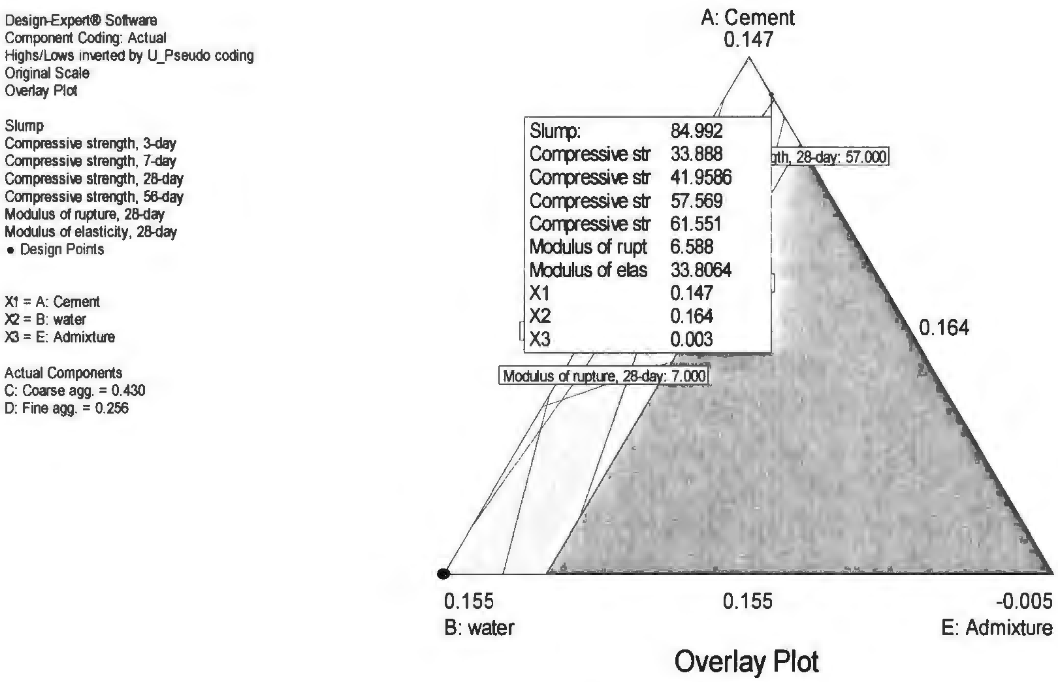

Figure 4.15. Overlay Contour Plot for Cement, Water, and HRWRA

Beyond four components, the counter plots become awkward, because only the level of three components at a time can be changed and the other components are sets at fixed conditions. In order to determine the appropriate properties, several trial and errors are required to obtain the best factor combinations (Smith, 2005). Therefore, for multi-response experiments with more than four components, numerical optimization provides a more efficient approach to optimization.

4.3.2. Numerical Optimization (Desirability Optimization Methodology)

One of the popular approaches to the optimization of multiple responses was developed by Derringer and Suich (1980). This numerical approach makes the use of desirability functions. The general approach involves the conversion of each responses y_i into an individual desirability function, d_i, that varies over the interval $0 \leq d_i \leq 1$. If the response y_i is in its acceptable ranges, then $d_i = 1$, and if the response is outside of it, $d_i = 0$.

Then, the overall desirability, D, is defined as a geometric mean of the individual desirability function d_i over the feasible region of mixture to measure the satisfaction of combined goals for all responses as follows:

$$D=(d_1\, d_2 d_3 \ldots\, d_2\,)^{1/n} \qquad [4.1]$$

where "n" is the number of responses in the mixture.

Depending on the objective for the responses, the individual desirability functions can be defined as "minimum, maximum, target, in range, and equal to a value". Also, the limitation on the lower and upper level of each component can be set. For simultaneous optimization, it is possible to place more emphasize on the upper and lower bounds or to emphasize on the target value by selecting additional parameters called weights that can be altered from 0.1 to 10. When the weight is equal to 1, the desirability function is linear. Choosing weight greater than 1 places more emphasis on the goal, weight less than 1 makes the goal less important. Furthermore, in the desirability objective function D, each response can be assigned an importance relative to the other responses. The importance (r_i) varies from the least importance (+) a value of one, to the most importance (+++++); a value of 5. If varying degree of importance are assigned to the responses, the overall desirability, D, is as follow:

$$D=(d_1^{r_1} \times d_2^{r_2} \times \ldots \times d_n^{r_n})^{1/\sum r_i} = \left(\prod_{i=1}^{n} d_i^{r_i}\right)^{1/\sum r_i} \qquad [4.2]$$

where “n” is the number of responses in the mixture. The numerical optimization finds a point that maximizes desirability function in either Equations 4.1 or 4.2 based on the goal and constraints on the responses.

4.3.3. Selection of Optimum Binder Combinations for Defined Criteria

The desired performance criteria are given in Table 3.1 in Chapter 3. Using the numerical optimization based on defined ranges and defined target values (Tables 3.1 and 4.1), the three mixtures are designed.

In the task of concrete optimization, the optimum mixture is chosen based on its economical and mechanical properties as well as durability properties. Hence, cost has an important role in the optimization procedure as well as other performance criteria. Therefore, in the current study the optimum mixture is designed and selected based on both highest desirability function and lowest cost. An approximate unit cost of the raw materials was obtained from a local supplier for a cubic meter of concrete.

Table 4.2 shows the three optimized mixtures with an estimate of unit cost of one cubic meter of each mixture. The mixture that maximizes overall desirability and has the lowest cost is highlighted in Table 4.2. The overall desirability function for this mix is 0.9.

Table 4.2. Predicted Mixtures for Optimum Binder Combination and Cost

Components						Compressive Strength						
Cement (kg/m³)	Water (kg/m³)	Coarse Agg. (kg/m³)	Fine Agg. (kg/m³)	HRWRA (lit/m³)	Slump (mm)	3-day (MPa)	28-day (MPa)	56-day (MPa)	Modulus of rupture 28-day (MPa)	Modulus of Elasticity 28-day (GPa)	Cost ($/m³)	Desirability
420	164	1127	671	3.3	85	33.89	57.57	61.55	6.59	33.8	184	0.9
432	164	1116	671	3.3	85	34.96	58.99	63.26	6.65	34.08	187	0.85
443	164	1106	671	4.4	85	35.96	60.31	64.84	6.71	34.35	196	0.72

The predicted response values are: slump = 85 mm, 3-day compressive strength = 33.89 MPa, 28-day compressive strength= 57.57 MPa, 56-day compressive strength= 61.55 MPa, 28-day modulus of rupture = 6.59 MPa, 28-day modulus of elasticity = 33.8 GPa, and cost =184 $\$/m^3$. The above concrete mixture was cast in order to validate the predicted properties and the results are illustrated in Table 4.7.

4.3.4. Validation of the Developed Models

Using numerical optimization (desirability function methodology) four mixtures are designed to satisfy specific properties of concrete. The concrete mixtures are selected to verify the accuracy of fitted models on the prediction of mix proportions. The tests are carried out with the same materials and under almost the same testing condition of the previous 20 mixtures used for development of statistical models. Tables 4.3 through 4.5 present the criteria that are used to design mix proportions and the final mix proportions are given in Table 4.6.

Table 4.3. Goals and Criteria of Verification Tests for Mixture Number V_1

Name	Goal	Lower Limit	Upper Limit	Importance
A: Cement (m^3)	is in range	0.1297	0.1552	3
B: Water (m^3)	is in range	0.1552	0.1638	3
C: Coarse aggregates. (m^3)	is in range	0.40668	0.43	3
D: Fine aggregates. (m^3)	is in range	0.2556	0.2556	3
E: Admixture (m^3)	is in range	0.00255	0.004	3
Slump (mm)	is target = 85	50	100	3
3-day compressive strength (MPa)	is target = 33	26	38.4	4
28-day compressive strength (MPa)	is target = 57	49.5	65	4
56-day compressive strength (MPa)	is target = 60	51.8	72.5	3
28-day modulus of rupture (MPa)	is target = 6.5	5.99	7.3	3
28-day modulus of elasticity (GPa)	Maximum	31.9	34	3

Table 4.4. Goals and Criteria of Verification Tests for Mixture Number V_2

Name	Goal	Lower Limit	Upper Limit	Importance
A: Cement (m^3)	is in range	0.1297	0.1552	3
B: Water (m^3)	is in range	0.1552	0.1638	3
C: Coarse aggregates. (m^3)	is in range	0.40668	0.43	3
D: Fine aggregates. (m^3)	is in range	0.2556	0.2556	3
E: Admixture (m^3)	is in range	0.00255	0.004	3
Slump (mm)	is target = 120	90	140	3
3-day compressive strength (MPa)	is target = 36	30	38.42	3
28-day compressive strength (MPa)	maximize	49.47	59	3
28-day modulus of rupture (MPa)	maximize	6.5	7.3	3
28-day modulus of elasticity (GPa)	maximize	31.94	34	3

Table 4.5. Goals and Criteria of Verification Tests for Mixture Number V_3

Name	Goal	Lower Limit	Upper Limit	Importance
A: Cement (m^3)	is target = 0.15	0.1297	0.1552	3
B: Water (m^3)	Maximum	0.1552	0.1638	3
C: Coarse aggregates. (m^3)	Maximum	0.40668	0.43	3
D: Fine aggregates. (m^3)	Minimum	0.2556	0.260	3
E: Admixture (m^3)	is in range	0.00255	0.004	3
Slump (mm)	is target = 110	50	150	3
3-day compressive strength (MPa)	is target = 34	28	38.42	4
7-day compressive strength (MPa)	is target = 40	36	48.25	3
28-day compressive strength (MPa)	is target = 61	50	65	4
56-day compressive strength (MPa)	is in range	55	72.57	3
3-day modulus of rupture (MPa)	is target = 4.25	3.49	5.02	3
7-day modulus of rupture (MPa)	is in range	4.5	6.02	3
28-day modulus of rupture (MPa)	is target = 6.6	5.99	7.3	3
28-day modulus of elasticity (GPa)	is target = 34	31.94	35	3

Table 4.6. Predicted Mix Proportions and Desirability Using Developed Models

Components	Mixture V_1	Mixture V_2	Mixture V_3
Cement (kg/m^3)	420	443	429
Water (kg/m^3)	164	163	164
Coarse aggregate (kg/m^3)	1126	1106	1118
Fine aggregate (kg/m^3)	671	671	671
HRWRA (ml/100 kg cement)	786	993	1020
Desirability	90%	74%	90%

The results of verification tests and 95 % prediction intervals on the responses of three mixtures are given in Tables 4.7 through 4.9. Except some responses, the results fall inside the prediction intervals. The predicted values of modulus of rupture (flexural strength) show that the models constructed work effectively; all the predicted values match well with the results from laboratory at all ages. The only exception is the flexural strength at 7-day of mixture V_3. The variations of compressive strength from the predicted values increase at later ages (28-day, 56-day, and 91-day) because these properties are not solely a function of mixture proportions. It can be affected by the curing condition (humidity and temperature). The proposed models for the compressive strength, the modulus of rupture, and the modulus of elasticity give good prediction for mixtures V_1 at all ages. Since the desirability function for mixture V_2 is around 70 %, it is expected that the results for this mixture have more variation form the predicted values. Also, there is no model for 3-day modulus of elasticity, the predicted values are based on the overall mean and cannot be reliable.

Table 4.7. Summary of Tests and Predicted Values for Mixture Number V_1

Responses	Predicted values	Experimental values	95 % Prediction interval	
			Lower limit	Upper limit
Slump (mm)	85	94	41	175
3-day compressive strength (MPa)	33.88	33.31	31.18	36.58
7-day compressive strength (MPa)	41.95	40.95	37.52	46.39
28-day compressive strength (MPa)	57.56	55.94	53.3	61.82
56-day compressive strength (MPa)	61.55	60.2	55.51	67.58
91-day compressive strength (MPa)	64.56	62.4	59.41	69.71
3-day modulus of rupture (MPa)	4.19	4.19	3.62	4.75
7-day modulus of rupture (MPa)	4.95	5.08	4.42	5.49
28-day modulus of rupture (MPa)	6.58	6.32	6.09	7.08
56-day modulus of rupture (MPa)	6.97	6.70	6.51	7.43
3-day modulus of elasticity (GPa)	29.2	29.10	25.9	32.6
7-day modulus of elasticity (GPa)	31.5	33.00	29.5	33.5
28-day modulus of elasticity (GPa)	33.8	33.80	32.5	35
56-day modulus of elasticity (GPa)	34.5	34.80	33.2	35.9

Table 4.8. Summary of Tests and Predicted Values for Mixture Number V_2

Responses	Predicted values	Experimental values	95 % Prediction interval	
			Lower limit	Upper limit
Slump (mm)	117	130	57	239
3-day compressive strength (MPa)	36.2	33.63	33.5	38.8
7-day compressive strength (MPa)	44.7	41.83	40.3	49.15
28-day compressive strength (MPa)	61.3	54.77	57.1	65.58
56-day compressive strength (MPa)	66.6	61.09	60.6	72.63
91-day compressive strength (MPa)	66.6	64.30	61.4	71.77
3-day modulus of rupture (MPa)	4.4	4.10	3.84	4.96
7-day modulus of rupture (MPa)	5.32	5.16	4.79	5.85
28-day modulus of rupture (MPa)	6.71	6.55	6.21	7.2
56-day modulus of rupture (MPa)	7.24	7.26	6.77	7.69
3-day modulus of elasticity (GPa)	29.7	28.14	26.4	33
7-day modulus of elasticity (GPa)	32.5	29.26	30.5	34.4
28-day modulus of elasticity (GPa)	34.1	33.80	33.1	35.6
56-day modulus of elasticity (GPa)	34.8	34	33.5	36.1

Table 4.9. Summary of Tests and Predicted Values for Mixture Number V_3

Responses	Predicted values	Experimental values	95 % Prediction interval	
			Lower limit	Upper limit
Slump (mm)	110	115	54	224
3-day compressive strength (MPa)	34.58	33.16	31.91	37.25
7-day compressive strength (MPa)	42.71	39.38	38.33	47.1
28-day compressive strength (MPa)	59.04	55.77	54.83	63.24
56-day compressive strength (MPa)	63.67	58.73	57.71	69.63
91-day compressive strength (MPa)	65.04	62.54	59.91	70.17
3-day modulus of rupture (MPa)	4.22	4.27	3.66	4.78
7-day modulus of rupture (MPa)	5.06	4.50	4.54	5.59
28-day modulus of rupture (MPa)	6.59	6.79	6.1	7.08
56-day modulus of rupture (MPa)	7.04	6.92	6.58	7.5
3-day modulus of elasticity (GPa)	29.4	28.5	26.1	32.6
7-day modulus of elasticity (GPa)	31.9	30.3	30	33.8
28-day modulus of elasticity (GPa)	33.9	33.9	32.7	35.1
56-day modulus of elasticity (GPa)	34.5	34.2	33.3	35.9

4.4 General Application of the Methodology

The application of statistical mixture design methodology, as a case study, is described in Chapters 3 and 4. This method can be generalized as a guideline for designing and optimizing concrete mix proportion. The application of this method proves to be more sufficient for product design and development time in which data are not available. The mixture design methodology is not limited to specific type of concrete or a field application. It can be adjusted based on the requirement of the specified application, the type of materials, and the properties of interest. The main steps in this method are:

- **Select components**

Based on the type of concrete, availability of the materials and the properties of interest the constituent materials of concrete will be chosen.

- **Select performance criteria**

Prior to selecting the appropriate range for concrete components, the properties of interest should be defined. These criteria for a specified application help to select the more appropriate ranges. These properties could be fresh properties, hardened properties, or durability properties. Since cost is an important factor, especially when the numbers of materials increase in the concrete mix it could be chosen as a variable in the design.

- **Select range of components based on the desired field application**

The applied ranges could be determined according to the literature or the existing methods and guidelines. If there is no information, historical data from few number of trial batches (experiments) in the laboratory could help to establish the reliable ranges.

- **Design the trial batches**

The trial mixtures are developed using the mixture design method and alphabetical optimal criteria such as IV-optimal or D-optimal.

- **Develop prediction models**

In order to developed prediction models, data are collected from standard tests on specimens. The prediction models are developed as functions of the mixture components using the appropriate statistical concepts. These models adequately represent the fresh, hardened or durability properties of the concrete. Also, they are used to understand how mixture components affect the responses (using the trace plots) and to develop the optimum mixture.

- **Optimization**

One of the advantages of mixture design is providing the cost-effective means of concrete optimization. The graphical (contour plots) or numerical optimization (desirability function approach) is used to find the optimum mixture.

CHAPTER 5

STRENGTH GAIN OF BLENDED CEMENT AND ORDINARY PORTLAND CEMENT

5.1. Introduction

As stated in the previous chapters, the blended cement used in this research is blended of fly ash and silica fume and ordinary Portland cement (OPC). The twenty-five percent fly ash content in this blended cement reduces the early age strength. The strength gain of concrete is an important factor in the design of construction processes. In the first part of this chapter, some of the mechanical properties of this blended cement concrete are presented. In the second part, the compressive strength, the modulus of rupture and the modulus of elasticity gain of blended cement concrete are compared with ordinary Portland cement concrete. The compressive strength is studied at 3- 7- 28- 56- and 91-day,the flexural strength (modulus of rupture), and the modulus of elasticity are investigated at 3- 7- 28, and 56-day.

5.2. Mechanical Properties of Blended Cement Concrete

5.2.1. Modulus of Rupture versus Square and Cubic Root of Compressive Strength

Figures 5.1 illustrates the correlation between the modulus of rupture (flexural strength) of blended cement concrete and the square root of compressive strength at 28-day. The experimentally obtained results at a 95 % confidence interval can be expressed as:

$$f_r = 0.85\sqrt{f_c'} \quad [5.1]$$

where f_r is a flexural strength and f_c' is a compressive strength.

A comparison between the equation recommended by ACI 363R - 92 (Equation 5.2) and the experimentally determined values (Equation 5.1) shows that the coefficient for experimental values in the current study is slightly lower than ACI 363R - 92.

$$f_r = 0.94\sqrt{f_c'} \quad [5.2]$$

where f_r is a flexural strength and f_c' is a compressive strength.

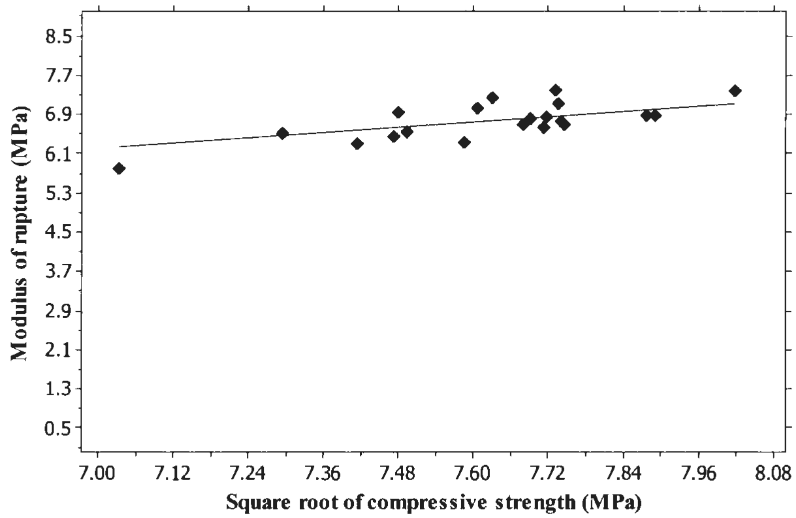

Figure 5.1.Modulus of Rupture versusSquare Root of Compressive Strength (Blended Cement)

Moreover, Khatri et al. (1995) reported a similar relationship between flexural strength and compressive strength. However, the value of the constant in that study was 0.81. In addition, they found that the flexural strength increased with the increase in the compressive strength at all ages. Hence, the results of the current research are in agreement with the findings of Khatri et al., (1995).

The correlation between modulus of rupture and cubic root of compressive strength at 28-day is plotted at Figure 5.2. The correlation coefficient (R^2) calculated for this relation is 0.40. This is lower than the $R^2 = 0.55$ for correlation between the modulus of rupture and the square root of compressive strength at 28-day (Figure 5.1).

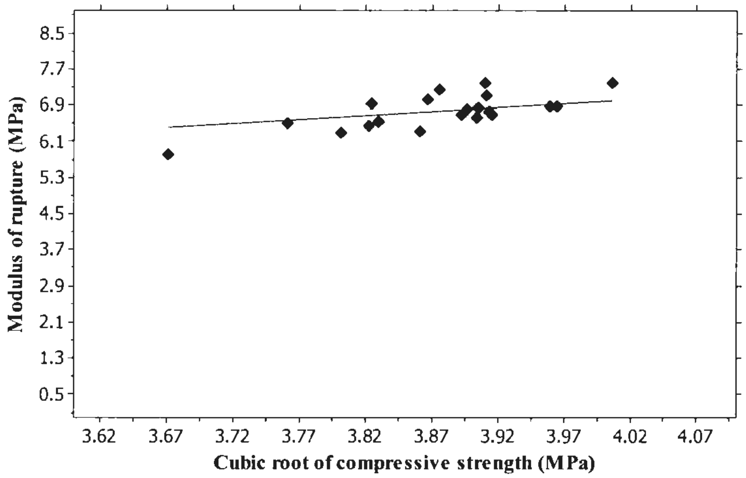

Figure 5.2. Modulus of Rupture versus Cubic Root of Compressive Strength (Blended Cement)

5.2.2. Modulus of Elasticity versus Square and Cubic Root of Compressive Strength

The modulus of elasticity versus the square root of compressive strength at 28-day is illustrated at Figure 5.3. The correlation relation is presented as:

$$E = 3536\sqrt{f_c'} + 7072 \quad \text{MPa} \qquad [5.3]$$

where E is modulus of elasticity and f'_c is compressive strength at 28-day.

A comparison of the experimentally obtained values and the modulus of elasticity predicted by expression recommended by ACI committee 363R-92 (reapproved 1997), which is presented in Equation 5.4, shows that the Equation 5.3 gives slightly higher values.

$$E = 3320\sqrt{f'_c} + 6900 \quad \text{MPa} \qquad [5.4]$$

where E is modulus of elasticity and f'_c is compressive strength at 28-day.

Figure 5.4 plots the modulus of elasticity versus cubic root of compressive strength at 28-day. The correlation coefficient (R^2) is 0.87. Plotting the modulus of elasticity versus square root of compressive strength at 28-day (Figure 5.3) shows weaker correlation (R^2 = 0.45) compared to the modulus of elasticity versus cubic root of compressive strength at 28-day.

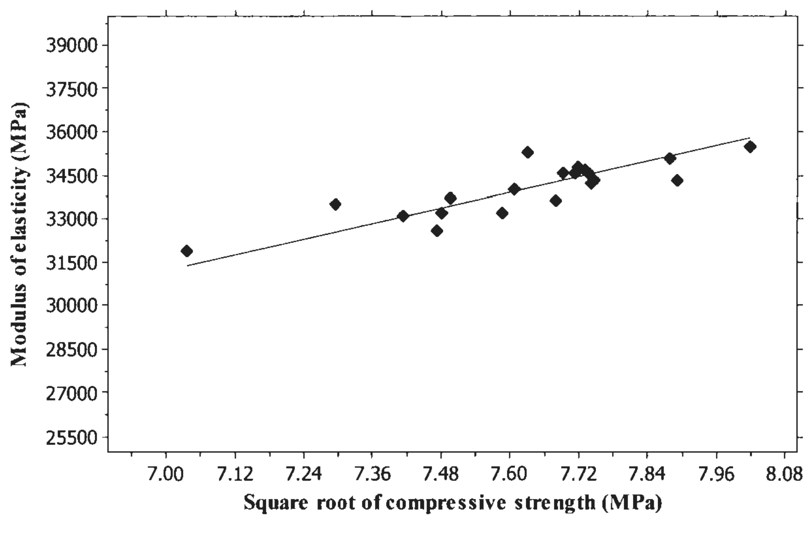

Figure 5.3. Modulus of Elasticity versus Square Root of Compressive Strength (Blended Cement)

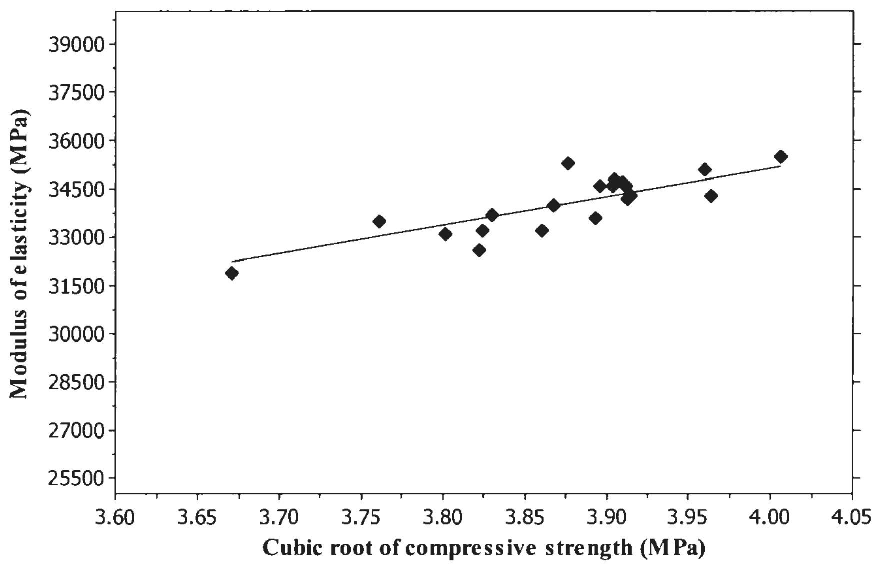

Figure 5.4. Modulus of Elasticity versus Cubic Root of Compressive Strength (Blended Cement)

The modulus of elasticity at 3- 7- 28- and 56-day are plotted against their compressive strength as shown in Figure 5.5.The modulus of elasticity, of all mixtures, increases with the increase in the compressive strength at all ages. This is in good agreement with the findings of Hooton (1993) and Khatri et al (1995). The modulus of elasticity of twenty mixtures indicate that there are considerable increase in modulus of elasticity from 7-day to 28-day. This follows with a moderate increasing rate after 28-day. As Gencel et al. (2012) stated, the results demonstrate that the effect of blended cement on modulus of elasticity is nominal compared to its effect on compressive strength.

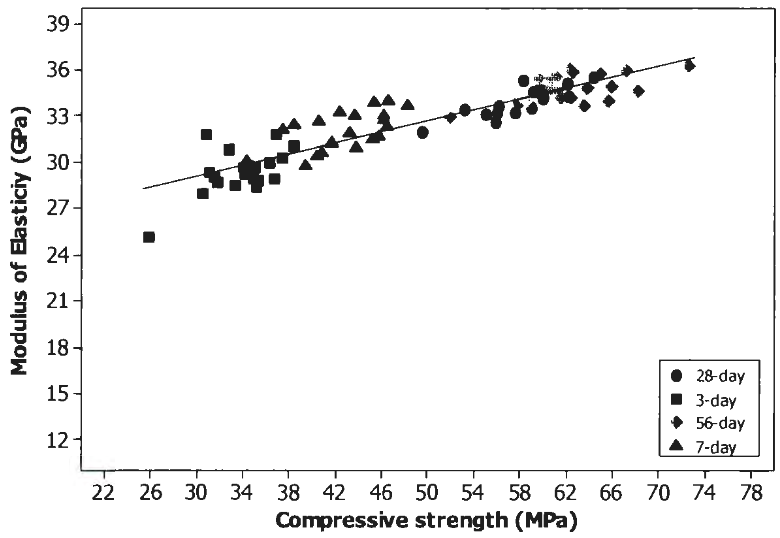

Figure 5.5. Modulus of Elasticity versus Compressive Strength (Blended Cement)

5.3. Comparison between Blended and Ordinary Portland Cement Concrete

5.3.1. Selection of Mixture Proportions

In addition to the 20 mixtures that are prepared for the statistical mixture design in Chapter 3, five mixes are selected to investigate the gain in compressive strength, modulus of rupture, modulus of elasticity, and the slump of blended cement and ordinary Portland cement (OPC) concrete. These five mixtures are selected based on the different levels of four factors (w/c ratio, cement content, coarse-to-fine aggregates ratio, and amount of HRWRA).

As the specific gravity of blended cement is 2.85 and the specific gravity of ordinary Portland cement is 3.15, special consideration is required to accurately compare these two types of cement. To this end, in order to have the same amount of cement in the mix proportions and to satisfy the ACI constraints (the volume fraction sum to unity), only the amount of coarse and fine aggregates is changed, while the ratio is kept the same for both types. All other mix components are kept the same for both type of cement. Table 5.1 presents the mix proportions for blended and OPC.

5.3.2. Results and Discussion

The results of the slump, the compressive strength, the modulus of rupture (flexural strength), and modulus of elasticity gain with time of the five different mixes of blended cement and conventional concrete are shown in Table 5.2.

Table 5.1. Concrete Mix Proportions for Blended Cement and OPC Concrete Mixtures

Mix No.	Constituent Material, kg/m^3				Admixture, (ml/100kg cement) -(lit/m^3)	Water-cement ratio	Coarse - Fine agg. ratio
	Cement Content	Water Content	Fine Aggregate	Coarse Aggregate			
• Blended Cement							
1	401	164	725	1088	1096- 4.4	0.41	1.50
2	444	155	670	1127	991- 4.4	0.35	1.68
5	415	164	674	1127	1061- 4.4	0.39	1.67
13	371	162	736	1111	980- 3.63	0.44	1.51
16	412	155	725	1101	952- 2.81	0.38	1.52
• Ordinary Portland Cement							
1	401	164	739	1108	1096	0.41	1.50
2	444	155	684	1150	991	0.35	1.68
5	415	164	687	1148	1061	0.39	1.67
13	371	162	749	1130	980	0.44	1.51
16	412	155	739	1122	952	0.38	1.52

Table 5.2 Test Results for Five Concrete Mixtures Using Blended and OPC Cements

		Compressive strength					Modulus of rupture				Modulus of elasticity			
Mix No.	Slump (mm)	3-day (MPa)	7-day (MPa)	28-day (MPa)	56-day (MPa)	91-day (MPa)	3-day (MPa)	7-day (MPa)	28-day (MPa)	56-day (MPa)	3-day (GPa)	7-day (GPa)	28-day (GPa)	56-day (GPa)
	• Blended Cement													
1	145	31.06	40.78	54.95	63.50	63.80	3.86	4.72	6.28	6.79	29.3	30.6	33.1	33.6
2	75	38.42	48.25	64.27	72.57	75.06	4.92	5.83	7.39	7.67	31.1	33.7	35.5	36.3
5	140	32.73	40.50	57.55	61.56	62.49	3.83	5.04	6.33	6.67	30.8	32.6	33.2	34.2
13	150	25.85	34.27	49.47	51.86	57.23	3.49	4.29	5.99	6.40	25.1	30	31.9	32.9
16	70	34.84	45.32	59.90	65.82	70.96	4.52	5.03	6.74	7.26	28.9	32.5	34.2	34.9
	• Ordinary Portland Cement													
1	145	37.9	42.13	49.45	57.18	___	5.35	5.61	6.11	6.39	29	29.6	32.2	33
2	54	48.73	51.93	61.23	66.23	69.54	6.22	6.79	7.05	7.29	32.3	32.8	33.8	35.4
5	125	42.29	46.47	53.48	57.1	58.01	5.25	5.99	6.18	6.57	30.7	32.1	32.8	32.4
13	140	35.18	38.8	46.23	51.17	55.83	5.1	5.29	5.57	6.1	31.2	31.5	32.1	33.9
16	48	44.71	48.01	60.97	64.45	65.1	5.1	5.92	6.33	6.75	30.9	32	34.4	34.9

5.3.2.1. Slump

In general, silica fume concrete has a lower flow than OPC concrete (Khatri et al., 1995). On the other hand, adding fly ash to silica fume concrete increases the workability of ternary concrete (Nassif et al., 2003). The flowability of concrete containing fly ash increases because the spherical particles of fly ash reduce the interfacial friction of fresh concrete (Gencel et al., 2012). The volume of a blended cement of fly ash and silica fume paste are greater than OPC concrete, and produces a larger cementitious paste volume with higher workability (Nawy, 2001).

The results of the slump tests of blended cement and OPC concrete are presented in Table 5.2. It can be observed that (based on equal binder content, w/c ratio, and the amount of HRWRA) all mixtures incorporating blended cement have slightly workability in fresh stage with the exception of mixture number 1.

5.3.2.2.Compressive Strength

The compressive strength development of concrete made with blended cement and ordinary Portland cement are shown in Figures 5.6 through 5.10. The early age (3- and 7-day) compressive strength of concrete incorporated of fly ash and silica fume is lower than that of conventional concrete (OPC) at the same cement content, regardless of w/c ratio and coarse-to-fine aggregates ratio. This is due to the small contribution of the pozzolanic activity of the fly ash at early ages. At 28-day and onward, when the hydration of Portland cement decreases, sufficient lime, which is produced during the hydration of cement, appears to be available to continue the pozzolanic reaction of fly ash to gain higher compressive strength (Nawy, 2001).

Figure 5.6 illustrates the compressive strength of mixture number 1 at 3- 7- 28- 56- and 91-day. Analyzing the results of mixture number 1 (with cement content of 401kg/m^3, w/c ratio of 0.41, and the lowest coarse-to-fine aggregates ratio of 1.5), it is evident that the compressive strength of blended cement is greater than that of OPC at the age of 28-day and onward. The compressive strength of blended cement is 11 % higher than OPC concrete at 28- and 56-day. However, at the early age (3-day) the compressive strength of blended cement is 18% less than OPC concrete while this difference is moderate at 7-day. The compressive strength of blended cement is 31.8 MPa and 40.8 MPa at 3- and 7-day, while the conventional concrete reaches 37.9 MPa and 42.1MPa after the same duration of moist curing.

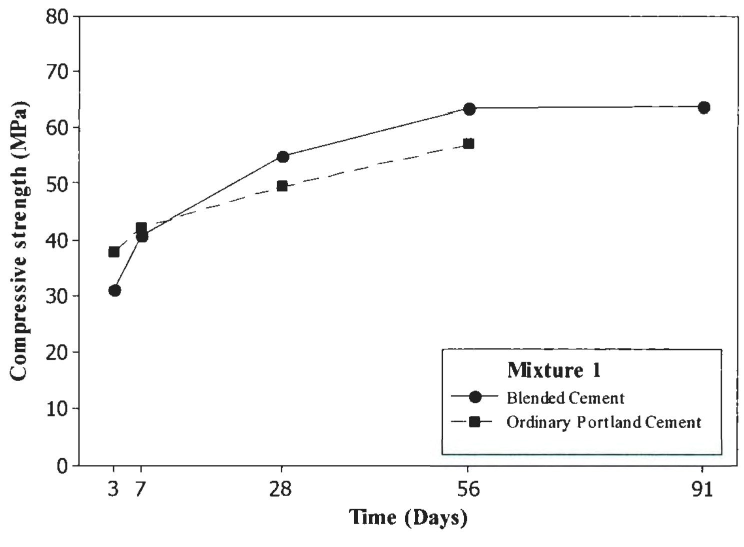

Figure 5.6.Compressive Strength Gain with Time of Mixture No. 1 (Blended and OPC)

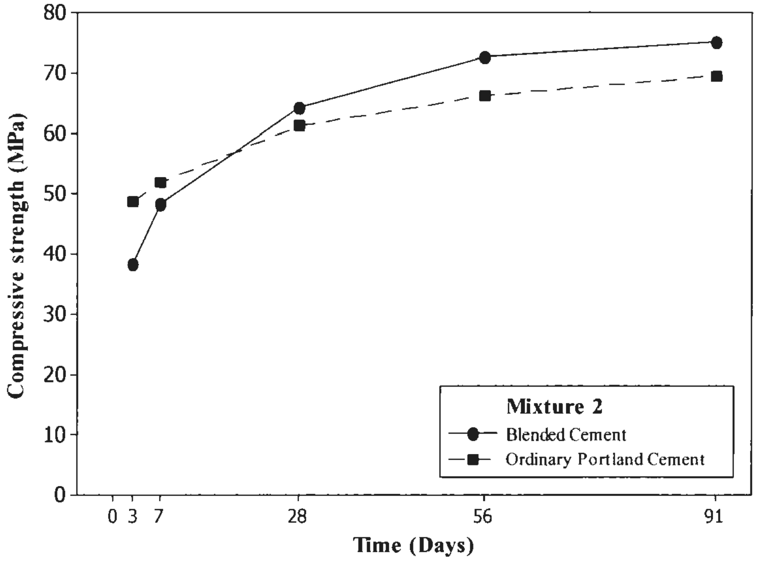

Figure 5.7.Compressive Strength Gain with Time of Mixture No. 2 (Blended and OPC)

Figure 5.7 illustrates the compressive strength of mixture number 2 at 3- 7- 28- 56- and 91-day. Mixture number 2 has the highest cement content (444 kg/m^3), the lowest w/c ratio (0.35), and the highest coarse-to-fine aggregates ratio (1.68). The results show that the 3-day compressive strength of blended cement is approximately 21% less than that of OPC concrete. This gap between strength gains decreases for the 7-day compressive strength. The blended cement attains 48.3MPa after 7 days, while OPC concrete reaches 51.9MPa. This means that the compressive strength of OPC concrete is 7.6 % higher than that of the blended cement concrete. According to Figure 5.7, it appears that they reach the same strength around 14 days after casting. Then, the blended cement specimens reach a higher strength at 28- 56- and 91-day. The increasing rate of compressive strength relative to 28-day is almost the same for both types of cement.

Figure 5.8 illustrates the compressive strength of mixture number 5 at 3- 7- 28- 56- and 91-day. Mixture number 5, made with blended cement, reaches 32.7 MPa and 40.5 MPa after 3-day and 7-day respectively. The same mix proportion, using ordinary Portland cement, reaches 42.3 MPa and 46.5 MPa after the same duration of curing. Hence, the compressive strength of blended cement are 22.6% and 12.8% less than the compressive strength of OPC concrete at 3- and 7-day, respectively. At 28-day, blended cement attains higher compressive strength compared to OPC concrete (approximately 7.6 % higher). As expected, the 56-day and 91-day compressive strength of blended cement concrete is higher than that of OPC for the same mixture. This is due to late contribution of fly ash on the compressive strength development of ternary concrete containing fly ash and silica fume.

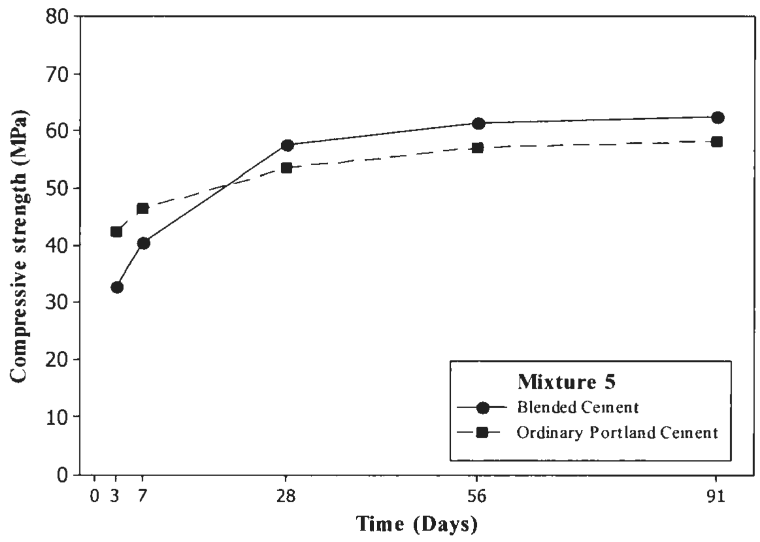

Figure 5.8. Compressive Strength Gain with Time of Mixture No.5 (Blended and OPC Cement)

Figure 5.9 shows the strength gain of mixture number 13 which has the lowest cement content (371 kg/m^3) and the highest w/c ratio (0.44). This mix has one of the lowest coarse-to-fine aggregates ratio (1.51) as well. From the results, it is observed that besides the lowest compressive strength at all ages compare to the other mixtures, the reduction in compressive strength gain of blended cement concrete is more pronounced. The compressive strength of blended cement concrete at 3- and 7-day is 26.5 % and 11.7 % less than that of OPC concrete. However, the early age (3- and 7-day) strength of blended cement concrete increases at a faster rate than the corresponding strength of OPC concrete. Comparing the compressive strength of these two types of concrete shows that for 28-day and onward the increasing trend of compressive strength is slower especially for blended cement.

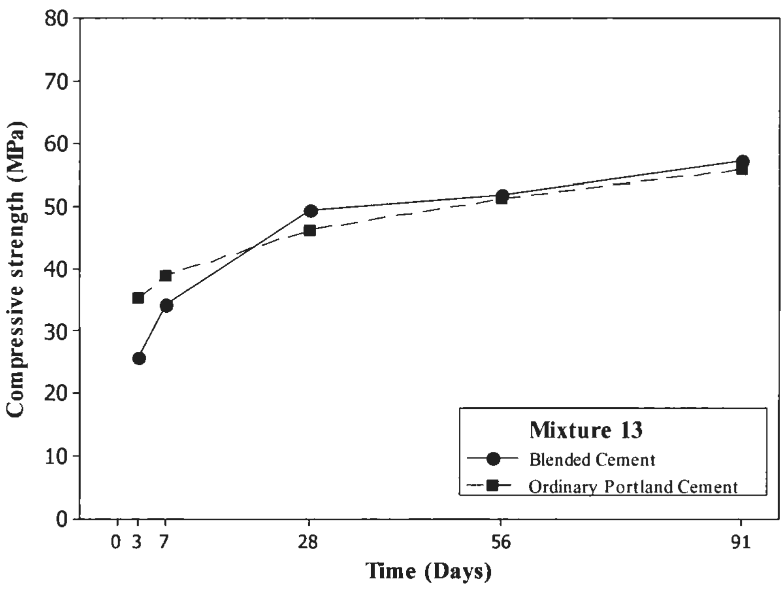

Figure 5.9. Compressive Strength Gain with Time of Mixture No. 13 (Blended and OPC)

Figure 5.10 illustrates the compressive strength gain of mixture number 16 for both OPC and blended cement concrete. As expected, at 3- and 7-day, the compressive strength of OPC concrete is higher than that of blended cement concrete for the same cement content of 412 kg/m^3. At 28-day and 56-day the compressive strength for both types of concrete is almost similar. By the age of 91 days, the compressive strength of blended cement concrete for this mixture becomes higher than that of OPC concrete.

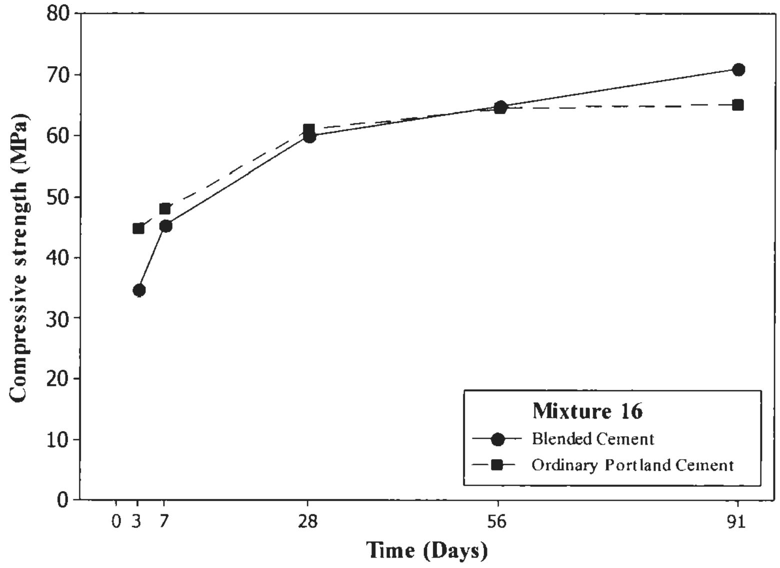

Figure 5.10. Compressive Strength Gain with Time of Mixture No. 16 (Blended and OPC)

In general, regardless of cement content, w/c ratio, and coarse-to-fine aggregates ratio, comparing the strength development of five mixtures of blended cement and OPC concretes shows that using blended cement decreased the strength gain at 3- and 7-day. However, compressive strength of concretes containing fly ash and silica fume become higher than OPC concrete from 28-day and onward. The results show that the effect of blended cement of fly ash and silica fume compounds to the compressive strength of specimens at later ages (56-day and 91-day) are more pronounced for high cement content mixes, except mixture number 16 at 56-day. The above results clearly indicates that the utilization of blended cement of fly ash and silica fume produce a ternary blend concrete with enhanced compressive strength at later ages. This is in agreement with the finding of Olek et al., 2002; Barbhuiya et al., 2009, and Nochaiya et al., 2010. They stated that fly ash contributes to strength development as concrete matures. It as an inert component at its early ages and it has a minor contribution in hydration. Also, silica fume improves the early age performance of concrete. It compensates for the slow pozzolanic reactivity of fly ash in early ages. Since the percentage of fly ash is more than silica fume in this type of cement (25% fly ash and 5% silica fume) the effect of fly ash is more pronounced than silica fume in strength development.

5.3.2.3.Modulus of Rupture

Figures 5.11 through 5.14 show the 3- 7- 28- and 56-day flexural strength (modulus of rupture) of blended cement and ordinary Portland cement concrete investigated in this study.

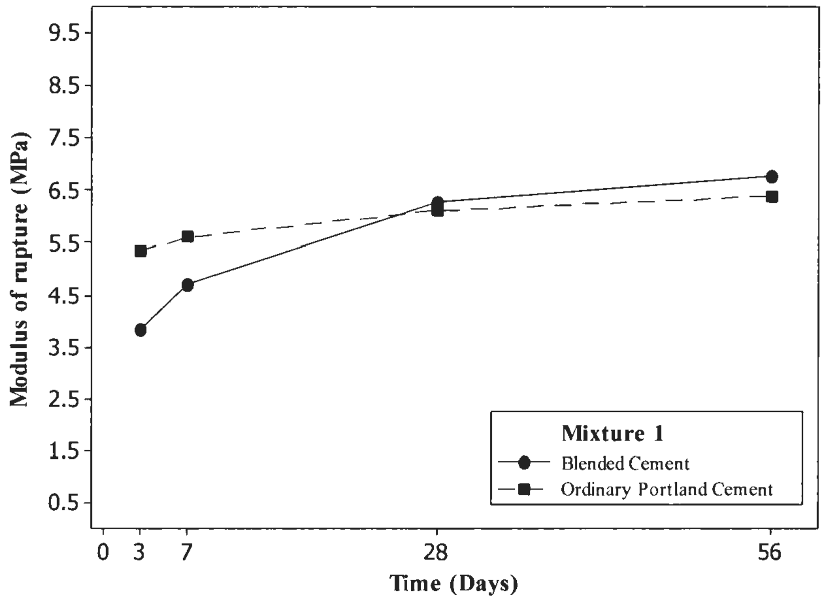

Figure 5.11. Modulus of Rupture Gain with Time of Mixture No. 1 (Blended and OPC)

By comparing the flexural strength gain of blended cement and OPC concrete for mixture number 1, it can be observed that using blended cement concrete significantly decreases flexural strength at 3-day and 7-day. The flexural strength, relative to the 28-day flexural strength, of both types of cement shows that OPC concrete reaches 87.5 % and 91.8 % of 28-day flexural strength after 3- and 7-day. The blended cement concrete reaches 61.5 % and 75.2 % of 28-day strength after 3-day and 7-day respectively. At 28-day and 56-day, blended cement concrete mixtures attains marginally higher flexural strength than those of the same OPC concrete.

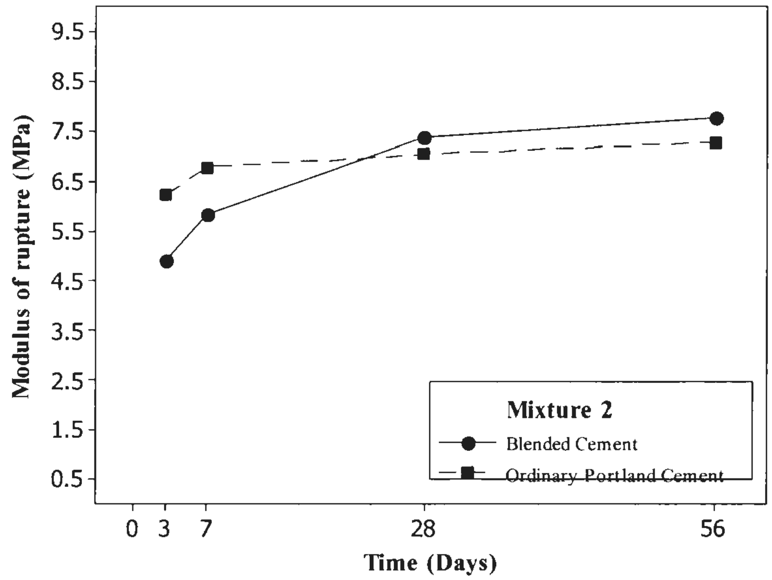

Figure 5.12. Modulus of Rupture Gain with Time of mixture No. 2 (Blended and OPC)

The flexural strength of mixture number 2, which has the highest cement content (444 kg /m^3), and the lowest w/c ratio (0.35), are illustrated at Figure 5.12. At 3- and 7-day, the flexural strength of Portland cement concrete is considerably higher than that of blended cement concrete. The relative strength data also indicates the high flexural value of OPC mixes compared to blended cement at 3- and 7-day. The strength reaches 88.2 % and 96.3% of the 28-day strength respectively. However, the strength of this mix with blended cement at both 28-day and 56-day exceeds that of OPC concrete. The increasing trend of flexural strength for blended cement concrete continues even after 56 days of curing. The flexural strength reaches 6.8 MPa after 56 days, which is still higher than the corresponding mix of OPC concrete with 6.4 MPa.

Mixture number 5 has one of the highest coarse-to-fine aggregates ratio and w/c ratio of 0.39. The results of the flexural strength (Figure 5.13) indicate that OPC concrete reaches 85 % and 97 % of 28-day compressive strength after 3 and 7 days of moist curing. While blended cement gains 60.5 % and 79.6 % of 28-day strength after 3- and 7-day respectively. Since OPC concrete reaches 97 % of 28-day strength after 7-day, there is no significant increase in strength at 28-day and 56-day. Blended cement attains 6.2 MPa after 28 days of curing; this is marginally higher than the control mix. In addition, there is no evidence of significant increase after 56 days of curing for both types of concrete.

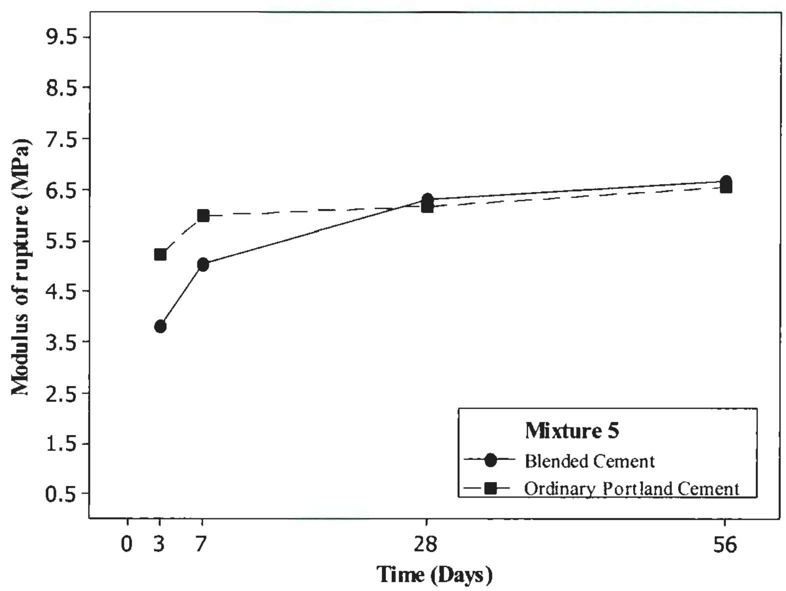

Figure 5.13. Modulus of Rupture Gain with Time of mixture No. 5 (Blended and OPC)

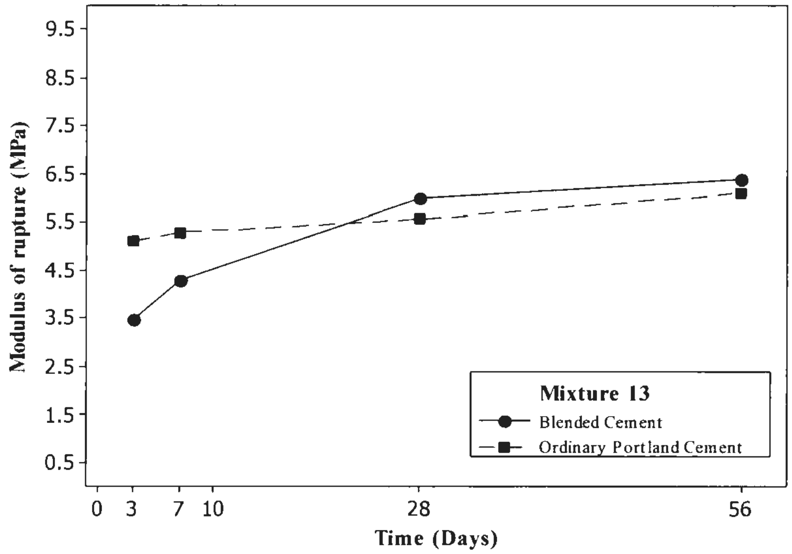

Figure 5.14. Modulus of Rupture gain with Time of mixture No.13 (Blended and OPC)

Figure 5.14 illustrates flexural strength gain of mixture number 13, which has the lowest cement content and highest w/c ratio. Likewise, compressive strength gain results show significant differences between flexural strength of blended cement and OPC concrete at 3- and 7-day. OPC concrete reaches91.6 % of the 28-day strength after 3-day (5.1 MPa). There is no evidence of significant increase later (5.3 MPa, 5.6 MPa and 6.1 MPa at 7- 28- and 56-day, respectively). Blended cement concrete only reaches 3.5 MPa after 3 days, which is 58.2 % of 28-day compressive strength. After 7 days of moist curing, there is a considerable increase in strength, which shows pozzolanic activity of fly ash in late strength gain. As presented in Figure 5.14, the flexural strength of blended cement at 28-day is 6 MPa which slightly increases to reach 6.4 MPa after 56 days of moist curing.

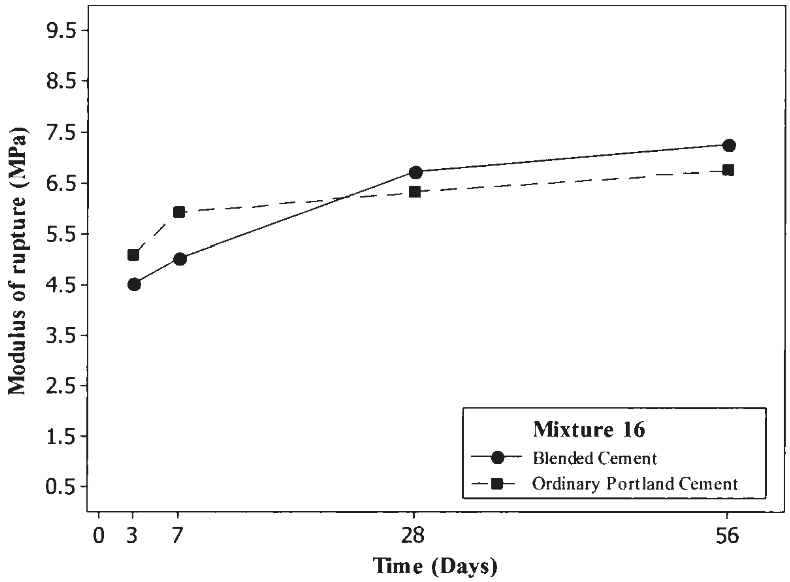

Figure 5.15. Modulus of Rupture Gain with Time of Mixture No.16 (Blended and OPC)

Figure 5.15 illustrates the flexural strength of mixture number16 at 3- 7- 28- and 56-day. As expected, the flexural strength of blended cement concrete at early ages is found to be lower than OPC concrete. Later at 28-day, the flexural strength of blended cement exceeds that of OPC concrete. The increasing trend of flexural strength continues for blended cement reaching 7.3 MPa at 56-day, where OPC concrete reaches lower strength (6.7 MPa) at the same date of curing. Regardless of different cement content, w/c ratio, or coarse-to-fine ratio, the results of all five mixtures generally indicate that the flexural strength of concrete prisms incorporation of blended cement at 3- and 7-day is lower than the control mixes of OPC. In addition, Flexural strength is found to increase with increasing compressive strength.

5.3.2.4.Modulus of Elasticity

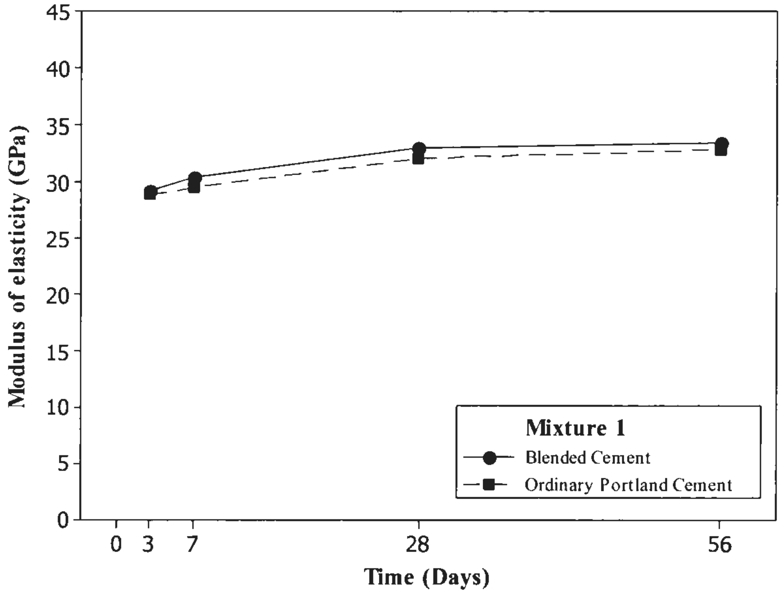

Figure 5.16. Modulus of Elasticity Gain with Time of Mixture No. 1 (Blended and OPC)

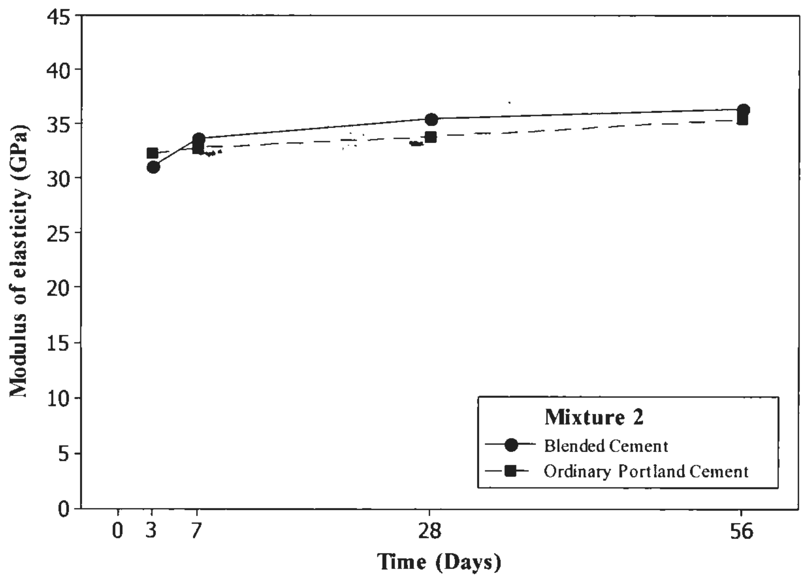

Figure 5.17. Modulus of Elasticity Gain with Time of Mixture No. 2 (Blended and OPC)

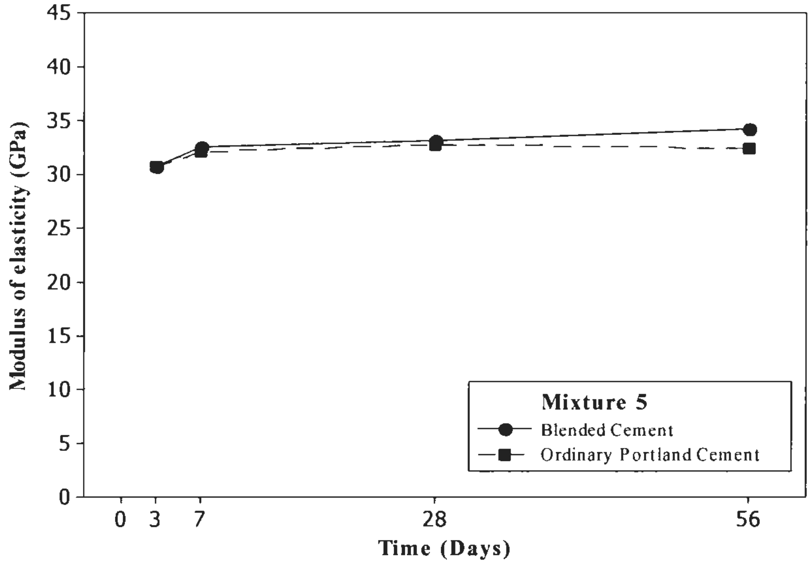

Figure 5.18.Modulus of Elasticity Gain with Time for Mixture N0.5 (Blended and OPC)

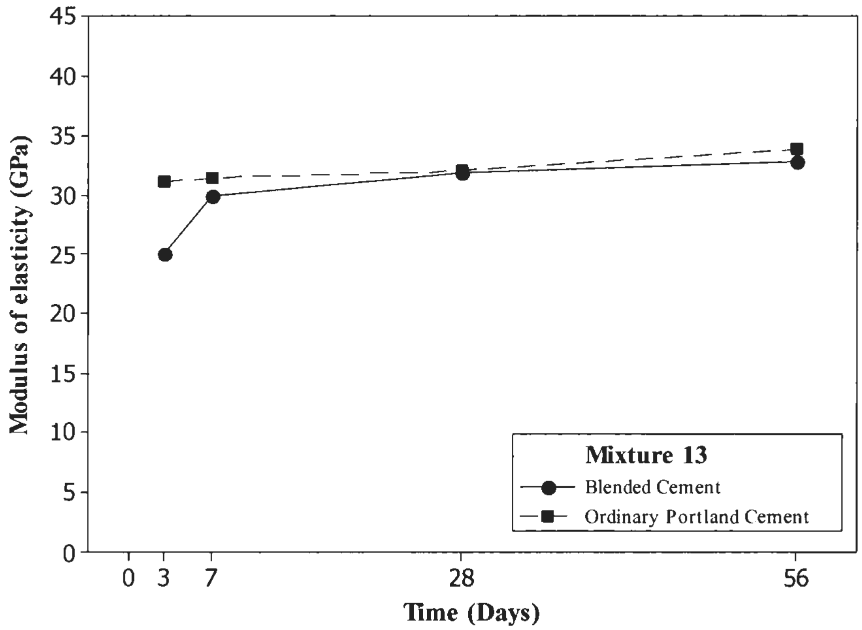

Figure 5.19.Modulus of Elasticity Gain with Time of Mixture No.13 (Blended and OPC)

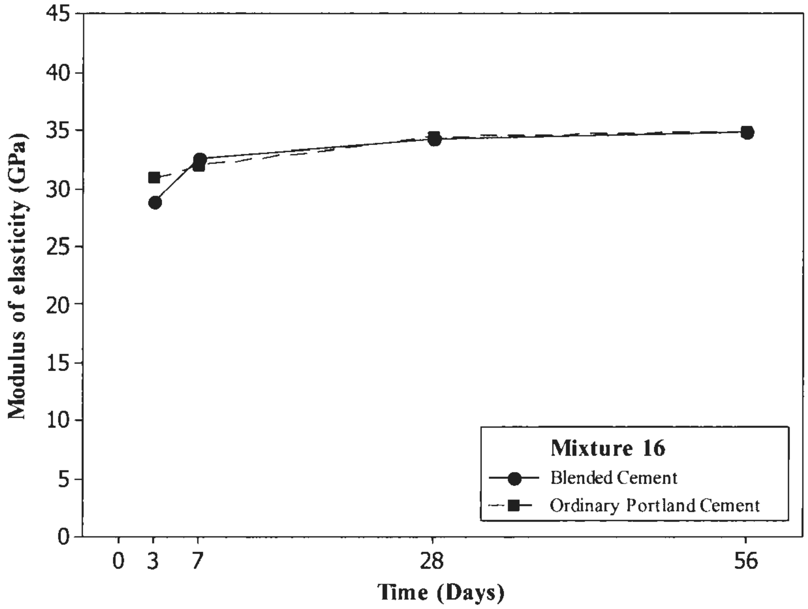

Figure 5.20. Modulus of Elasticity Gain with Time of Mixture No.16 (Blended and OPC)

Modulus of elasticity of the blended cement and OPC concrete at 3- 7- 28- 56-day for five mixtures are shown in Figures 5.16 through 5.20. The analyses of the results indicate that unlike the compressive and the flexural strength gain, there is a not substantial difference between blended cement and OPC concrete particularly at 28-day and 56-day.

CHAPTER 6

CONCLUSIONS

In practice, using traditional mix proportioning methods require many trial batches to generate the data that may identify the optimum mixture proportions. In the present research, statistical mixture design methodology is applied to optimize mix proportion of concrete instead. The mix proportions are designed to allow the development of an optimized mix proportion using IV-optimal design with a low number of trial batches. The results from trail batches are analyzed using an ordinary least-squares method and appropriate (Scheffé polynomial) models. The models adequately represent the fresh and hardened properties of concrete and are fitted to the measured results. The developed models are also utilized to graphically (contour and trace plots) and numerically (desirability function approach) predict concrete performances, and to optimize the mixture proportions which is the main goal of mixture design method. The following conclusions can be drawn from the present research.

- A database of 267 concrete mixtures of fly ash and silica fume from literature are provided to determine the component ranges.
- The statistical mixture method is used effectively to provide a simple and cost-effective approach for designing and optimizing of mix proportion of concrete with the lowest possible trial batches.
- The IV-Optimal criteria and mixture design approach are used to design20statistically designed trial batches for constrained region.

- The prediction models are established after casting the 20 mixtures for the 3- 7- 28- 56- and 91-day compressive strength, the 3- 7- 28- and 56-day modulus of rupture and modulus of elasticity using the mixture method. They are valid for mixtures with 372 to 443 kg/m^3 blended hydraulic cement, 155 to 164 kg/m^3 water, 1066 to 1127 kg/m^3 coarse aggregates, 671 to 736 kg/m^3 fine aggregates, and 3.3 to 4.4 liters of HRWRA.
- A linear model fitted all but two of the responses for the materials and condition of current study. The quadratic model fitted the 91-day compressive strength and the natural logarithm model fitted the slump better than the linear model. Furthermore, no model can fit the results of modulus of elasticity at 3-day.
- Numerical multi-optimization approach (desirability function approach) with the user controlling the goals of the optimization and significance of each experimental parameter is used to obtain the best component setting that leads to an optimum mix proportion. The proportion of components for the optimum mixture that maximizes overall desirability (D = 0.90) and has the lowest cost is cement content = 420 kg/m^3, water content = 164 kg/m^3, coarse aggregate content = 1126 kg/m^3, fine aggregate content = 671 kg/m^3, HRWRA = 786 ml/$_{\text{100kg cement}}$.
- Graphical trace and contour plots are used as simple visual tools to investigate the effect of each component and their blending effect on the mixture. Furthermore, overlay contour plots is also used to graphically predict or optimize the concrete mix proportion of defined performance criteria.

- The laboratory test results of compressive strength, flexural strength and modulus of elasticity at specified days for three more predicted mixtures fall within insides the prediction intervals except for a few tests. It can be confirmed that the conclusions drawn from the analyses are valid.

As a secondary objective, the performance characteristics of five mixtures (blended cement concrete) from the mixture design are compared with mixtures of similar proportions of ordinary Portland cement concrete. The following conclusions can be drawn from this part of research.

- The comparison between blended cement concrete and conventional concrete shows that the compressive strength and flexural strength of blended cement concrete are lower than ordinary Portland concrete at 3- and 7-day. From 28-day onwards the blended cement concretes reach higher strength than conventional concretes. The type of cement had no significant effect on the modulus of elasticity.
- The empirical equation for predicting modulus of elasticity obtained from experimental results give slightly higher value than the empirical formula suggested by ACI committee 363R-92.
- The value obtained for the relationship between flexural strength and square root of compressive strength is in agreement with the values reported by ACI committee 363R-92.

6.1 Recommendations

Some recommendations in the use of mixture design method that might be helpful for designing a better design space, and for fitting better prediction models, are as follows:

- It would be recommended to choose slightly wider components' ranges to draw better interpretation of the results.
- The mixture proportions that are suggested by the IV-optimal design are selected focusing on the accurate prediction of the models parameters. There is no specific consideration for covering all the design space. Extra care is required to generate a satisfactory distribution of information that covers the entire design space not only part of it.
- The lowest number of center points and replications are used in designing the trial batches because of time and cost issues. The results show that some models have small R^2, R^2_{pred} and large standard deviations. To this end, it might be useful to augment the design to increase the accuracy of the models or to fit higher order models with at least special cubic terms.
- Terms like w/c ratio or coarse-to-fine aggregates ratio is widely used in the concrete mix proportion. It would also be possible to work with the ratio of the mixture components instead of the original component proportions to design trail batches using mixture design approach.

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Note: The references that are marked with "*" symbol are used to create a database of concrete mixtures containing silica fume and fly ash in Chapter 2.

APPENDICES

Appendix A – Database of concrete mixtures in the literature containing fly ash and silica fume

An extensive review of publications that used silica fume and fly ash as cementitious materials are collected to create a following database. Table A.1 shows the general information related to the studied papers and table A.2 gives information on the mix proportions and the result of performed tests corresponding to each paper in the Table A.1.

Table A.1 General Information About the Papers in the Database

Row	Reference	frequency of Ternary mixtures	Cement type	Fly Ash Class	Silica fume form	Test performed	Experimentation methodology	Curing condition	Air entrained
1	Carette, G., & Malhotra, V. M. (1983)	24 out of 36	Type I	Class F	Condensed	Slump Compressive strength (3- 7- 28- 56- and 91-day) Flexural strength (7- and 14-day)	Trial and error	Standard (23° C and 100% humidity)	Yes

[Contin.] Table A.1 General Information About the Papers in the Database

Row	Reference	frequency of Ternary mixtures	Cement type	Fly Ash Class	Silica fume form	Test performed	Experimentation methodology	Curing condition	Air entrained
2	Baoyu, L. et al., (1989)	13 out of 17	425R, 525R (early-age strength)	Class F	Condensed	Slump Compressive strength (3- 7- 28- and 91-day) Modulus of Elasticity (28-day) Tensile strength (3- 7- 28- and 91-day) Adiabatic calorimetry Abrasion resistance Permeability Ultimate elongation	Trial and error	Standard (23° C and 100% humidity)	No
[3-1]	Celik Ozyildirim and Woodrow J. Halstead (1995)	8 out of 10	Type II	Class F		Slump Compressive strength (1- 7- and 28-day) Rapid Chloride permeability (RCP)	Trial and error	Different curing temperatures and durations of moist-curing	Yes
[3-2]	Celik Ozyildirim and Woodrow J. Halstead (1995)	8 out of 8	Type III	Class F		Slump Compressive strength (1- 7- and 28-day) Rapid Chloride permeability	Trial and error	Different curing temperature and durations of moist-curing	Yes

[Contin.] Table A.1 General Information About the Papers in the Database

Row	Reference	frequency of Ternary mixtures	Cement type	Fly Ash Class	Silica fume form	Test performed	Experimentation methodology	Curing condition	Air entrained
4	Khatri and Sirivivatnanon 1995	2 out of 7	Type I	Class F		Slump Compressive strength (3- 7- and 28-day) Flexural strength (28-day) Modulus of Elasticity (28-day)	Trial and error	Standard (23° C and 100% humidity)	No
5	Sujit Ghosh et al. (1996)	2 out of 2	Type I	Class C	Condensed	Compressive strength (7- 28- and 56-day) Modulus of Elasticity (28-day)	Trial and error	Standard then high temperature and pressure	No
6	Bajorski, P., et al., (1997).	15 out of 15	OPC	Class F		Slump Compressive strength (3- 7- 14- and 28-day) Permeability Plastic shrinkage and resistance to cracking Scaling	Three-factor central composite design	29.5° C and 40% relative humidity	Yes
7	Jones, M. R., Dhir, R. K., & Magee, B. J. (1997)	5 out of 22	Portland cement	Polwriz-ed fly ash		Compressive strength (28-day) chloride-ion penetration	Trial and error	Standard (23° C and 100% humidity)	No

[Contin.] Table A.1 General Information About the Papers in the Database

Row	Reference	frequency of Ternary mixtures	Cement type	Fly Ash Class	Silica fume form	Test performed	Experimentation methodology	Curing condition	Air entrained
8	Lam, L.,et al., (1998)	6 out of 24	Type l	Class F	Condensed	Compressive strength (28- and 56-day) Tensile splitting strength	Trial and error	27° C in water according to Hong Kong practice	No
9	Thomas M.D.A. et al., (1999)	1 out of 4	Type l	Fly ash with low CaO		Compressive strength (1- 3- 7- 14- 28- and 56-day) durability	Trial and error		
10	Bajorski, P., & Streeter, D. A. (2000).	24 out of 24	Ordinary Portland cement	Class F		Slump Compressive strength (3- 7- 14- and 28-day) RCP test Plastic shrinkage Cracking and scaling	Box–Behnken design		Yes
11	Olek, J. et al., (2002).		Type I	Class C	EMSAC, Type F-100 in powder form	Slump Compressive strength (3- 7- 28- and 56-day) Modulus of Elasticity (28- and 56-day) RCP test and Chloride conductivity test DC resistance Absorption Other durability tests	Response surface methodology (RSM)	Standard (23° C and 100% humidity)	No except two mixtures

[Contin.] Table A.1 General Information About the Papers in the Database

Row	Reference	frequency of Ternary mixtures	Cement type	Fly Ash Class	Silica fume form	Test performed	Experimentation methodology	Curing condition	Air entrained
12	Nassif, N., and Suksawang, N. (2003)	50 out of 87	Type I	Class F	FORCE. 1000D	Slump Compressive strength (1- 3- 7- 14- 28- and 56-day) Modulus of Elasticity (28- and 56-day) Drying shrinkage Creep from comp. load Chloride permeability test Scaling	Trial and error	-Moist curing -Air drying -Burlap curing -Curing compound	
13	Bouzoubaâ et al., (2004)	28 out of 48	Type I Type F	Class F and C	Silicon metal fume from Niagara Falls	Slump Compressive strength (1- 7- 28- and 91-day) Chloride-ion penetration	Trial and error	Standard (23° C and 100% humidity)	Yes
14	Lawler, et al.. (2005)	4 out of 10	Type I	Class F and C		Slump Compressive strength (3- 7- 28- and 56-day) Modulus of elasticity (28- and 56-day) Fresh property tests and Durability tests	Statistical design and analysis of experiments (three level)	Standard (23° C and 100% humidity)	

[Contin.] Table A.1 General Information About the Papers in the Database

Row	Reference	frequency of Ternary mixtures	Cement type	Fly Ash Class	Silica fume form	Test performed	Experimentation methodology	Curing condition	Air entrained
15	Tahir Gonen et al., (2007)	1 out of 5	Portland cement grade 42.5			Slump Compressive strength (7- 28- 90- 180- and 360-day) Durability tests	Trial and error	-Air dry -wet curing	
16	Ramazan Demirboga (2007)	1 out of 6	Tape I			Compressive strength (3- 7- 28- 90- and 120-day) Thermal conductivity test	Trial and error	Standard (23° C and 100% humidity)	No
17	Panchalan and Ramakrishnan (2007)	3 out of 10	Type I/II	Class F	Densified	Compressive strength (14- and 28-day) Flexural strength (14- and 28-day) Rapid chloride permeability test	Trial and error	Standard and Accelerate-d (at 38°C for 7 days)	Yes
18	Barbhuiya et al. (2009)	2 out of 6	Ordinary Portland cement class 42.5 N			Slump Compressive strength (3- 7- and 28-day) Air permeability and Porosity Thermal analysis	Trial and error	Standard (23° C and 100% humidity)	

Contin.] Table A.1 General Information About the Papers in the Database

Row	Reference	frequency of Ternary mixtures	Cement type	Fly Ash Class	Silica fume form	Test performed	Experimentation methodology	Curing condition	Air entrained
19	Chinnaraju et al., (2010)		Ordinary Portland cement	Class F		Compressive strength (7- and 28-day) Flexural strength (28-day) Tensile splitting strength (28-day)	Trial and error	Standard (23° C and 100% humidity)	
20	Yilmaz kocak (2010)	2 out of 10	Portland cement			Compressive strength (1-7- 28- 56- and 90-day) water demand Physical Analysis	Trial and error	Standard (23° C and 100% humidity)	
21	Radlinski, M., and J. Olek, (2010)		Type I	Class C		Slump Compressive strength (28-day) Durability tests	RSM	Standard for data reported in this data base	Yes
22	Nochaiya et al., (2010).	3 out of 7	Type I			Compressive strength (7- 14- 28- and 60-day)	Trial and error	Standard (23° C and 100% humidity)	
23	Muthupriya et al., (2011)	3 out of 7	Ordinary Portland cement			Compressive strength (3- 7- 28- 56- and 90-day) Flexural strength (28-day)	Trial and error		

Contin.] Table A.1 General Information About the Papers in the Database

Row	Reference	frequency of Ternary mixtures	Cement type	Fly Ash Class	Silica fume form	Test performed	Experimentation methodology	Curing condition	Air entrained
24	Radlinski, M., &Olek, J. (2012)	1 out of 4	Type I	Class C		Compressive strength (1- 3- 7- 28- and 180-day) Synergistic effect Water sorptivity	Trial and error	0-7 days at 23°C, 7-56 days at 38°C.	
25	Hariharan A. R. et al., (2011)	6 out of 12	Type I	Class C	un compacted	Slump Compressive strength (1- 3- 7- 28- and 91-day) Rapid chloride permeability test	Trial and error	Standard (23° C and 100% humidity)	No

Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
1	263	113	30	18	5	394	0.40	158	1115	683	4.9	11.2	22.2	28.5		40.4			5.0	5.4			65		
	265	113	30	39	10	417	0.40	167	1102	675	5.2	15.6	25.7	35.3		46.8			5.4	6.8			55		
	263	113	30	56	15	432	0.40	173	1084	664	5	16.2	27.4	39.1		49.0			5.3	6.6			55		
	262	113	30	75	20	450	0.40	180	1066	653	5	16.4	28.8	41.0		53.0			6.1	6.9			75		
	209	90	30	15	5	314	0.50	157	1114	747	6.6	5.9	13.7	19.7		30.6			3.8	4.3			90		
	209	90	30	30	10	329	0.50	165	1104	736	6.5	9.5	17.8	27.1		37.6			4.3	5.0			85		
	206	88	30	45	15	339	0.50	170	1098	711	6.8	9.3	17.7	29.1		41.5			4.0	4.9			90		
	208	90	30	60	20	358	0.50	179	1076	718	6.2	10.9	20.1	31.7		46.5			4.6	6.2			90		
	172	74	30	13	5	259	0.60	155	1114	806	6.1	3.7	9.5	14.8		27.0			3.3	4.4			95		
	171	74	30	24	10	269	0.60	161	1104	799	6.4	6.0	12.6	18.4		31.0			3.5	4.2			70		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition: Fly ash content		Binder composition: Silica fume content		Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	172	74	30	37	15	283	0.60	170	1100	797	5.7	6.9	14.4	22.5		34.3			3.6	4.3			70		
1	172	74	30	49	20	295	0.60	177	1090	788	5.6	7.0	13.6	24.4		36.6			3.8	4.9			70		
	149	63	30	11	5	223	0.70	156	1083	851	6.5	2.3	6.5	10.6		20.4			2.2	3.1			85		
	148	63	30	21	10	232	0.70	162	1071	841	6.5	2.8	7.5	12.8		24.3			2.5	3.6			90		
	149	63	30	32	15	244	0.70	171	1064	837	6.5	3.4	8.1	14.5		27.5			2.5	3.7			90		
	149	63	30	43	20	255	0.70	179	1058	832	6	3.8	9.5	18.7		32.4			3.1	4.7			90		
	131	56	30	10	5	197	0.80	158	1062	905	6.5	1.8	5.1	8.4		16.6			2.1	2.8			90		
	131	56	30	18	10	205	0.80	164	1054	898	6.3	2.1	5.4	9.3		19.6			2.0	2.9			75		
	130	55	30	28	15	213	0.80	170	1036	883	6.6	2.4	5.9	10.7		21.7			2.3	3.2			95		
	130	56	30	37	20	223	0.80	178	1031	878	6.4	2.7	6.3	12.6		22.8			2.4	3.5			90		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m³)	Binder composition: Fly ash content, kg/m³	Binder composition: Fly ash content, % by mass of binder	Binder composition: Silica fume content, kg/m³	Binder composition: Silica fume content, % by mass of binder	Total Binder (kg/m³)	W/CM	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Air %	Compressive Strength (MPa): 1-day, may 2- day	Compressive Strength (MPa): 3-day	Compressive Strength (MPa): 7-day	Compressive Strength (MPa): 14-day	Compressive Strength (MPa): 28-day	Compressive Strength (MPa): 56-day	Compressive Strength (MPa): 91-day,90-day	Flexural Strength (MPa): 7-day	Flexural Strength (MPa): 14-day	Flexural Strength (MPa): 28-day	Flexural Strength (MPa): 56-day	Slump(mm)	E (GPa): 28-day	E (GPa): 56-day
	171	73	30	13	5	257	0.60	154	1106	800	6.8	4.0	9.6	14.7		23.5	27.5	29.0					80		
	170	72	30	24	10	266	0.60	160	1096	793	7	4.3	11.2	18.1		29.4	31.9	35.2					75		
	169	72	30	36	15	277	0.60	166	1076	779	7	5.1	11.8	21.9		31.4	35.1	36.4					75		
	170	72	30	49	20	291	0.60	175	1078	779	6.1	6.3	13.3	22.2		30.5	36.3	37.8					55		
2	166	41	19	14	7	226	0.52	116	1427	672			13.2	19.2		36.3		45.4					80		
	152	40	23	14	7	215	0.53	114	1441	663			12.2	17.8		33.8		45.2					79	31	
	140	60	28	14	7	228	0.52	119	1435	654			11.7	15.4		32.7		44.5					77		
	183	61	23	17	7	267	0.42	112	1408	662				24.7		44.1		56.1					90		
	183	61	23	26	10	267	0.39	104	1408	662				29.4		54.8		71.1					92		
	166	61	25	16	7	252	0.46	116	1416	667				23.1		44.0		55.2					94		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition: Fly ash content kg/m^3	Binder composition: Fly ash content % by mass of binder	Binder composition: Silica fume content kg/m^3	Binder composition: Silica fume content % by mass of binder	Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa) 1-day, may 2- day	Compressive Strength (MPa) 3-day	Compressive Strength (MPa) 7-day	Compressive Strength (MPa) 14-day	Compressive Strength (MPa) 28-day	Compressive Strength (MPa) 56-day	Compressive Strength (MPa) 91-day,90-day	Flexural Strength (MPa) 7-day	Flexural Strength (MPa) 14-day	Flexural Strength (MPa) 28-day	Flexural Strength (MPa) 56-day	Slump(mm)	E (GPa) 28-day	E (GPa) 56-day
	157	61	25	23	10	243	0.44	107	1418	668				25.7		45.9		57.0					88		
3-1	232	114	32	11	3	357	0.44	157	1109	657	6.5	10.1		20.5		35.0							95		
	232	93	26	32	9	357	0.44	157	1109	657	8	10.8		23.7		35.9							90		
	193	141	40	18	5	352	0.44	155	1109	657	5.6	7.6		17.7		32.1							90		
	193	122	35	36	10	351	0.44	154	1109	657	7.8	9.5		19.0		36.3							80		
3-1	211	123	60	18	5	352	0.40	141	1109	619	6.5	12.3		23.3		37.9							90		
	213	124	60	18	5	355	0.45	160	1109	570	7.5	8.8		19.7		32.5							100		
	231	106	65	18	5	355	0.40	142	1109	619	6.2	13.7		26.1		39.0							85		
	231	106	65	18	5	355	0.45	160	1109	570	7.5	10.1		20.8		35.8							80		
3-2	232	114	32	11	3	357	0.44	157	1109	657	5.8	15.9		26.8		40.3							80		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	193	141	40	18	5	352	0.44	155	1109	657	5.2	11.8		23.7		35.2							90		
	193	122	35	36	10	351	0.44	154	1109	657	7.9	9.9		21.9		32.3							75		
	211	123	60	18	5	352	0.40	141	1109	619	6.3	17.8		36.4		39.6							85		
	213	124	60	18	5	355	0.45	160	1109	570	7.1	13.2		22.1		35.2							100		
	231	106	65	18	5	355	0.40	142	1109	619	6.3	18.4		29.4		43.4							90		
	231	106	65	18	5	355	0.46	163	1109	570	6.3	14.3		23.4		36.3							90		
4	320	65	15	45	10	430	0.34	146	1087	718	1.4		37.0	50.5		76.0					7.4	8.8	160	35	
	282	106	25	46	10	434	0.34	148	1094	708	1.8		32.0	47.0		76.0					7.1	9.0	120	37	
5	287	80	20	40		407	0.27	110						57.1		72.1	69.3							42	
	117	234	60	39		390	0.27	105						33.2		54.1	54.8							41	

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m³)	Binder composition: Fly ash content kg/m³	Binder composition: Fly ash content % by mass of binder	Binder composition: Silica fume content kg/m³	Binder composition: Silica fume content % by mass of binder	Total Binder (kg/m³)	W/CM	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Air %	Compressive Strength (MPa) 1-day, may 2- day	Compressive Strength (MPa) 3-day	Compressive Strength (MPa) 7-day	Compressive Strength (MPa) 14-day	Compressive Strength (MPa) 28-day	Compressive Strength (MPa) 56-day	Compressive Strength (MPa) 91-day,90-day	Flexural Strength (MPa) 7-day	Flexural Strength (MPa) 14-day	Flexural Strength (MPa) 28-day	Flexural Strength (MPa) 56-day	Slump(mm)	E (GPa) 28-day	E (GPa) 56-day
6	290	78	20	24	6	392					9		23.6	27.0	31.9	38.6							67		
	289	56	15	30	8	375					7.4		21.0	28.4	36.4	38.6							73		
	289	56	25	30	8	375					8.7		16.4	24.6	32.8	41.9							70		
	316	62	15	33	8	410					9.5		19.9	25.9	31.6	39.2							105		
	316	62	25	33	8	410					8.9		13.9	24.1	30.2	36.7							92		
	302	59	10	31	10	392					6.3		27.4	39.7	49.3	53.2							83		
	302	59	30	31	10	392					6.1		18.4	25.6	35.0	39.3							51		
	275	54	20	29	10	357					9.8		17.4	26.5	35.3	39.4							76		
6	330	64	20	34	10	428					5.7		19.8	28.7	36.7	41.7							83		
	302	59	20	31	10	392					6.4		20.8	28.5	35.6	41.6							64		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition: Fly ash content		Binder composition: Silica fume content		Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	289	56	15	30	12	375					6.6		24.6	33.5	42.2	45.5							35		
	289	56	25	30	12	375					7.9		20.4	29.1	41.0	47.6							86		
	316	62	15	33	12	410					5.5		23.7	30.9	38.8	42.5							44		
	316	62	25	33	12	410					5.6		15.1	26.9	35.5	41.1							64		
	302	59	20	31	14	392					5.8		16.4	24.4	37.0	42.1							44		
7	180	20	10	20	10	220	0.84	185	1200	725	na					20.0									
	140	140	45	30	10	310	0.60	185	1200	580						20.0									
	250	30	10	30	10	310	0.60	185	1200	615						40.0									
	220	220	45	45	10	485	0.38	185	1200	410						40.0									
	260	260	45	65	10	585	0.32	185	1200	355						60.0									

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
8	400	80	20	20	5	500	0.30	150	1086	686						84.2	86.5								
	345	138	40	17	5	500	0.30	150	1086	654						71.6	76.1								
	320	64	20	16	5	400	0.40	160	1157	662						56.2	61.7								
	276	110	40	14	5	400	0.40	160	1157	636						40.5	47.3								
	328	66	20	16	5	410	0.50	205	1132	578						46.8	53.1								
	283	113	40	14	5	410	0.50	205	1132	578						33.2	37.4								
9			25		8							8.0	20.0	30.0	37.0	46.0	50.0								
10	280	42	15	28	10	350					11		18.6	27.3	33.4	37.0							60		
	259	65	25	26	10	350					11		16.7	20.6	28.3	32.1							85		
	271	41	15	38	14	350					9.7		23.7	28.3	35.9	39.6							80		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	**Binder composition**				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	**Compressive Strength (MPa)**							**Flexural Strength (MPa)**				Slump(mm)	**E (GPa)**	
		Fly ash content		**Silica fume content**																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	252	63	25	35	14	350					6		19.4	29.6	37.1	42.9							45		
	251	50	20	25	10	326					6.8		22.7	34.4	42.4	45.9							50		
10	288	58	20	29	10	375					7.6		21.0	30.6	38.5	45.2							45		
	243	49	20	34	14	326					8.6		19.4	24.7	34.2	37.1							70		
	279	56	20	39	14	374					9.9		18.2	24.1	31.1	35.2							100		
	257	38	15	31	12	326					6.5		25.6	31.0	38.5	43.9							45		
	295	44	15	35	12	374					8.8		19.8	28.5	33.5	39.2							135		
	238	59	25	39	12	336					6.7		20.7	28.8	37.0	41.9							45		
	273	68	25	33	12	374					7		22.2	28.1	35.1	40.2							55		
	265	53	20	32	12	350					9.2		22.4	28.2	36.9	41.7							55		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	246	74	30	30	12	350					7.9		16.9	21.3	28.8	34.1							85		
	287	29	10	34	12	350					7.2		26.4	33.7	42.5	46.1							40		
	330	66	20	13	4	409					6.7		22.0	28.3	33.0	39.2							65		
	344	69	20	14	4	427					7.1		17.7	24.3	28.3	33.0							100		
10	294	103	35	12	4	409					7.1		10.2	23.5	26.9	34.1							85		
	307	107	35	12	4	426					9		10.2	17.3	22.1	28.1							155		
	325	65	20	19	6	409					6.3		22.5	29.5	33.7	41.8							50		
	339	68	20	20	6	427					6.5		20.5	27.2	32.7	37.8							55		
	290	101	35	18	6	409					8.8		11.5	17.8	23.2	27.0							123		
	303	106	35	18	6	427					7.2		na	18.2	24.4	27.5							100		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition: Fly ash content		Binder composition: Silica fume content		Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	315	87	28	16	5	418					7.7		17.4	25.5	30.8	36.8							90		
11	293	78		20		390	0.40	156	1100	740				44.2		60.0	63.4							31	34
	322	39		29		390	0.45	176	1100	697				41.7		62.8	59.8							33	34
	244	117		29		390	0.45	176	1100	673				48.3		59.2	66.0							34	37
	341	39		10		390	0.45	176	1100	705				46.1		52.4	59.1							34	37
	263	117		10		390	0.45	176	1100	681				43.9		66.1	65.6							33	37
11	322	39		29		390	0.35	137	1100	798				69.6		83.1	88.1							34	34
	244	117		29		390	0.35	137	1100	775				64.9		84.1	84.5							34	40
	341	39		10		390	0.35	137	1100	806				68.5		84.7	84.2							36	38
	263	117		10		390	0.35	137	1100	783				58.0		77.7	83.7							39	41

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	293	78		20		390	0.50	195	1100	638				40.8		55.8	56.0							31	32
	215	156		20		390	0.40	156	1100	716				47.2		65.4	67.8							36	39
	293	78		20		390	0.30	117	1100	841				73.3		92.6	96.6							40	41
	273	78		39		390	0.40	156	1100	732				52.4		68.6	71.2							35	37
	269		25		6	390	0.40	156	1049	669	6.3	9	26.6	37.3		51.0	61.2						152	29	30
	211		40		6	390	0.40	156	1049	661	6.4		21.3	30.3		47.0	54.2						165	25	26
12	A		15		7		0.44				2.5	12.4	22.7	29.8	33.9	42.8	45.6						38		
			10		5		0.44				4.3	13.8	25.1	33.1	37.3	42.9	48.6						57		
12			15		5		0.44				2.5	10.2	23.4	31.9	35.9	42.4	49.1						46		
			20		5		0.44				4	10,7	22.0	29.7	35.9	42.4	49.1						51		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition: Fly ash content		Binder composition: Silica fume content		Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
			25		5		0.44				3.5	12.7	21.6	27.2	32.0	38.8	42.8						57		
			18		9		0.44				3.3	13.3	22.2	28.8	35.2	41.7	45.7						38		
			20		10		0.44				3	10.3	21.5	30.3	36.1	43.8	47.5						38		
			20		15		0.44				3.5	12.8	21.6	29.6	33.4	44.9	47.7						38		
	B		15		7		0.39				7.5	13.9	25.1	33.5	40.5	47.0	55.1						146		
			10		5		0.39				6.5	21.4	28.8	37.3	40.2	47.0	51.4						121		
			15		5		0.39				5.3	16.2	27.5	35.1	41.3	46.3	53.8						76		
			20		5		0.39				6	15.4	22.4	27.9	35.4	40.0	48.1						152		
			25		5		0.39				3.5	16.3	28.3	33.0	39.2	48.2	45.7						81		
			18		9		0.39				3	19.0	27.7	37.1	44.2	51.6	56.7						76		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
12			20		10		0.39				3	18.0	26.5	36.3	42.1	49.0	53.6						51		
	BN		15		7		0.35				5	30.7	44.1	55.4	60.4	67.1	69.7						140		
			10		5		0.35				4	37.1	45.7	53.6	58.5	67.6	71.2						102		
			15		5		0.35				4.5		42.9	52.5	60.1	63.7	66.7						76		
			25		5		0.35				4.3		32.0	39.5	45.0	48.1	54.1						89		
			18		9		0.35				4		37.9	47.1	54.2	59.7	66.6						89		
			20		15		0.35				2		33.7	42.6	52.5	56.5	63.5						76		
	C		15		7		0.37				1.8		31.5	37.1	42.4	50.7	56.8	60.6					25		
			10		5		0.37				5		35.6	42.0	48.4	58.4	64.4	66.7					76		
			15		5		0.37				4	22.1	32.7	39.4	46.1	53.0	59.4	62.0					25		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition: Fly ash content kg/m^3	Fly ash content % by mass of binder	Silica fume content kg/m^3	Silica fume content % by mass of binder	Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa) 1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	Flexural Strength (MPa) 7-day	14-day	28-day	56-day	Slump(mm)	E (GPa) 28-day	56-day
			20		5		0.37				6	21.8	30.4	36.9	42.9	50.6	59.2	60.0					95		
			25		5		0.37				8.5	17.2	25.5	31.3	39.1	42.3	53.2	55.9					228		
12			18		9		0.37				4.2	19.7	27.9	34.1	41.4	46.4	54.0	55.4					44		
			20		10		0.37				4		26.2	34.1	41.3	47.1	53.0	57.1					19		
			20		15		0.37				4	19.4	26.7	34.6	42.3	49.1	55.1	57.2					19		
	D		15		7		0.33				4		47.3	55.7	61.7	70.1	72.6	72.4					89		
			10		5		0.33				4		42.8	52.0	56.7	65.2	71.0	67.9					102		
			15		5		0.33				4		47.6	55.8	60.3	67.2	73.2	75.3					89		
			20		5		0.33				3.5	37.3	43.4	51.3	57.8	59.6	71.6	74.8					89		
			25		5		0.33				4.5		38.4	45.5	50.1	59.8	64.7	65.2					140		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
			18		9		0.33				3.3	28.7	37.4	43.6	50.8	59.0	65.1	67.8					13		
			20		10		0.33				3.5		37.0	44.9	52.3	60.6	68.2	71.3					25		
			20		15		0.33				3	33.7	41.6	46.4	55.2	60.2	63.0	67.7					38		
	G		15		7		0.29				3.5		74.1	57.5	63.1	73.3	78.8	81.2					102		
12			10		5		0.29				3		52.4	62.0	66.5	69.6	81.3	84.3					44		
			15		5		0.29				3		50.9	59.8	64.6	68.3	76.9	84.1					136		
			20		5		0.29				3.5	38.7	45.3	54.3	59.0	67.8	75.3	76.1					140		
			25		5		0.29				3		42.4	48.5	57.2	63.2	75.2	70.4					102		
			18		9		0.29				3		49.9	55.8	61.3	69.9	72.0	80.2					102		
			20		10		0.29				3.5		45.7	52.9	59.5	66.2	75.0	76.3					82		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition: Fly ash content: kg/m^3	Binder composition: Fly ash content: % by mass of binder	Binder composition: Silica fume content: kg/m^3	Binder composition: Silica fume content: % by mass of binder	Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa): 1-day, may 2- day	Compressive Strength (MPa): 3-day	Compressive Strength (MPa): 7-day	Compressive Strength (MPa): 14-day	Compressive Strength (MPa): 28-day	Compressive Strength (MPa): 56-day	Compressive Strength (MPa): 91-day,90-day	Flexural Strength (MPa): 7-day	Flexural Strength (MPa): 14-day	Flexural Strength (MPa): 28-day	Flexural Strength (MPa): 56-day	Slump(mm)	E (GPa): 28-day	E (GPa): 56-day
			20		15		0.29				3.5		40.6	49.9	59.8	63.6	65.1	68.7					89		
			30		5		0.40					19.0	26.7	31.9	38.5	44.0	51.4	52.8							
			35		5		0.40					15.5	22.0	26.5	34.2	40.6	46.5	49.2							
			15		7		0.37					24.5	32.8	39.7	44.1	52.3	58.5	61.6							
			18		9		0.37					21.1	30.2	37.5	44.7	55.1	57.2	62.0							
			15		7		0.30					36.5	42.7	54.2	62.0	70.0	73.8	77.2							
			10		5		0.30					36.1	47.0	54.5	59.6	64.9	69.7	75.1							
13	267	70	20	14	4	351	0.40	140	1103	736	6.8	19.8		37.3		48.2		51.7					140		
	255	71	20	28	8	354	0.40	142	1109	740	7.2	17.8		37.1		47.3		49.4					130		
	236	107	30	14	4	357	0.40	143	1116	743	6	12.2		33.4		47.0		51.0					140		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m³)	Binder composition				Total Binder (kg/m³)	W/CM	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m³	% by mass of binder	kg/m³	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	221	107	30	28	8	356	0.40	142	1108	738	6.4	12.5		33.9		46.6		51.3					130		
	195	139	40	14	4	348	0.40	139	1080	721	7.3	7.7		26.5		41.0		47.4					130		
	184	141	40	28	8	353	0.40	141	1094	729	7.4	7.6		24.8		39.4		45.2					110		
	265	70	20	14	4	349	0.40	140	1097	732	7.6	15.5		33.4		41.6		49.1					120		
	254	71	20	28	8	353	0.40	141	1110	740	7	15.8		35.8		-		52.6					130		
	232	107	30	14	4	353	0.40	141	1110	740	6.2	15.2		33.8		44.3		50.9					130		
	219	107	30	28	8	354	0.40	142	1109	739	6.4	14.3		33.5		46.1		53.2					120		
	199	142	40	14	4	355	0.40	142	1109	739	6	10.4		28.6		42.3		49.2					130		
13	186	143	40	29	8	358	0.40	143	1116	743	6	9.6		28.4		43.0		50.0					145		
	272	72	20	14	4	358	0.40	143	1131	754	5.5	16.3		40.5		53.3		59.4					145		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	259	72	20	29	8	360	0.40	144	1130	753	5.6	17.0		42.5		56.1		61.1					110		
	235	108	30	14	4	357	0.40	143	1124	748	5.6	12.2		41.2		52.8		60.0					140		
	224	110	30	29	8	363	0.40	145	1135	758	5	12.1		42.2		56.0		64.8					140		
	200	143	40	14	4	357	0.40	143	1115	744	5	5.9		33.6		52.2		63.9					130		
	188	145	40	29	8	362	0.40	145	1129	752	5	5.7		32.0		49.0		59.4					120		
	301	137	30	18	4	456	0.34	155	1027	684	7	17.6		40.2		48.9		54.8					100		
	283	138	30	37	8	458	0.34	156	1027	684	7.1	16.2		43.6		51.4		57.3					150		
	257	184	40	18	4	459	0.34	156	1024	682	6.8	15.4		34.5		49.6		56.0					180		
	241	185	40	37	8	463	0.34	157	1031	687	6.2	14.5		35.3		51.7		59.1					140		
	212	229	50	18	4	459	0.34	156	1016	677	6.6	10.6		30.7		43.0		50.9					150		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m³)	Binder composition: Fly ash content kg/m³	Fly ash content % by mass of binder	Silica fume content kg/m³	Silica fume content % by mass of binder	Total Binder (kg/m³)	W/CM	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Air %	Compressive Strength (MPa) 1-day, may 2- day	Compressive Strength (MPa) 3-day	Compressive Strength (MPa) 7-day	Compressive Strength (MPa) 14-day	Compressive Strength (MPa) 28-day	Compressive Strength (MPa) 56-day	Compressive Strength (MPa) 91-day,90-day	Flexural Strength (MPa) 7-day	Flexural Strength (MPa) 14-day	Flexural Strength (MPa) 28-day	Flexural Strength (MPa) 56-day	Slump(mm)	E (GPa) 28-day	E (GPa) 56-day
13	195	229	50	37	8	461	0.34	157	1016	677	7	10.1		29.9		41.7		48.0					170		
	257	183	40	18	4	458	0.34	156	1033	688	6.4	18.2		34.1		48.3		54.0					150		
	241	185	40	37	8	463	0.34	157	1040	693	6	16.9		35.6		48.9		56.7					160		
	259	185	40	19	4	463	0.34	157	1045	697	5.8	15.6		39.9		55.8		63.7					160		
	242	186	40	37	8	465	0.34	158	1045	698	5.9	13.8		40.4		56.9		63.0					135		
14	264	94	25	19	5	377	0.37	139	971	745	7.8			32.6		43.4	46.5						196	26	32
	202	155	40	31	8	388	0.37	144	1002	757	6.2			24.3		42.0	48.8						147	23	33
	306	58	15	19	5	383	0.37	142	987	754	6.9		25.6	34.5		44.3	49.8						147	25	30
	256	96	25	31	8	383	0.45	173	988	658	7.4		12.0	18.8		28.4	32.8						165	22	25
15			20		10									50.0		59.0		65.0					60		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
16	298	26	7.5	26	7.5	350	0.35	168	1035	740			25.4	35.6		52.7									
17	301	70	17	32	8	403	0.39	156	1018	649	5.4				35.0	43.0				4.2	5.8				
17	309	70	17	23	6	402	0.39	156	1018	649	4.4				40.0	50.0				5.1	5.8				
	290	93	23	23	6	406	0.38	156	1018	649	6.8				30.0	35.0				4.0	5.8				
18	333	299	50	17	na	649	0.30	195	1014	545	na		23.0	32.0		49.0							20		
	404	161	30	20		585	0.35	202	1059	570			30.0	39.0		59.0							50		
19	525	58	10	15	2.5	583	0.32	187	1235	523				54.0		71.2									
	466	117	20	15	2.5	583	0.32	187	1235	523				54.0		73.5									
	531	175	30	15	2.5	583	0.32	187	1235	523				51.5		71.0									
	525	58	10	29	5	583	0.32	187	1235	523				55.5		72.5									

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition: Fly ash content kg/m^3	Binder composition: Fly ash content % by mass of binder	Binder composition: Silica fume content kg/m^3	Binder composition: Silica fume content % by mass of binder	Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa) 1-day, may 2- day	Compressive Strength (MPa) 3-day	Compressive Strength (MPa) 7-day	Compressive Strength (MPa) 14-day	Compressive Strength (MPa) 28-day	Compressive Strength (MPa) 56-day	Compressive Strength (MPa) 91-day,90-day	Flexural Strength (MPa) 7-day	Flexural Strength (MPa) 14-day	Flexural Strength (MPa) 28-day	Flexural Strength (MPa) 56-day	Slump(mm)	E (GPa) 28-day	E (GPa) 56-day
	466	117	20	29	5	583	0.32	187	1235	523				57.5		76.0									
	531	175	30	29	5	583	0.32	187	1235	523				51.5		72.0									
	525	58	10	44	7.5	583	0.32	187	1235	523				57.0		74.5									
	466	117	20	44	7.5	583	0.32	187	1235	523				58.0		77.5									
19	531	175	30	44	7.5	583	0.32	187	1235	523				51.8		73.1									
	525	58	10	58	10	583	0.32	187	1235	523				57.5		78.5									
	466	117	20	58	10	583	0.32	187	1235	523				60.5		79.1									
	540	175	30	58	10	583	0.32	187	1235	523				52.8		75.9									
	525	58	10	73	13	583	0.32	187	1235	523				55.0		73.0									
	466	117	20	73	13	583	0.32	187	1235	523				57.5		74.5									

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m³)	Binder composition				Total Binder (kg/m³)	W/CM	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m³	% by mass of binder	kg/m³	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	531	175	30	73	13	583	0.32	187	1235	523				51.0		70.5									
20			5				0.50					26.1		39.9		53.1	57.9	63.9							
			10				0.50					19.8		32.7		52.9	57.1	58.2							
21	231	62	20	15	5	308	0.41	126	1116	747						43.6									
	231	62	20	15	5	308	0.41	126	1142	739						48.5									
	231	63	20	22	7	317	0.41	130	1104	738						48.3									
21	231	63	20	22	7	317	0.41	130	1129	720						49.1									
	231	107	30	18	5	356	0.41	146	1055	706						45.8									
	231	107	30	18	5	356	0.41	146	1072	695						44.3									
	231	110	30	26	7	367	0.41	151	1040	696						41.4									

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m^3)	Binder composition				Total Binder (kg/m^3)	W/CM	Water (kg/m^3)	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Air %	Compressive Strength (MPa)							Flexural Strength (MPa)				Slump(mm)	E (GPa)	
		Fly ash content		Silica fume content																					
		kg/m^3	% by mass of binder	kg/m^3	% by mass of binder							1-day, may 2- day	3-day	7-day	14-day	28-day	56-day	91-day,90-day	7-day	14-day	28-day	56-day		28-day	56-day
	231	110	30	26	7	367	0.41	151	1063	688						46.9									
	249	66	20	17	5	332	0.40	133	1062	778				41.0	50.0	58.0	62.0						135		
22	320	36	10	18	5	374	0.56	209	1218	607				27.0	34.0	40.0	45.0								
	280	70	20	35	10	385	0.56	216	1200	598				27.0	36.0	42.0	48.0								
	243	104	30	35	10	382	0.56	214	1192	594				23.0	28.5	36.0	45.0								
23	486	57	10	29	5	572	0.30	171	1172	577	na		33.7	42.3		58.7	68.7	74.3			5.7				
	472	57	10	43	7.5	572	0.30	171	1172	572			31.3	41.0		57.3	68.3	60.3			5.4				
	457	57	10	57	10	572	0.30	171	1172	567			29.0	39.3		55.3	60.3	67.3			5.9				
24	332	89	20	22	5	443	0.41	182		1590		15.0	30.0	42.0		55.0									
25	180	144	40	36	10	360	0.40	144	1138	726		17.0	27.0	35.0		46.0		54.0					15		

[Contin.] Table A.2 Database of Mix Proportions and the Results of Performed Tests

Row	Cement content(kg/m³)	Binder composition: Fly ash content kg/m³	Binder composition: Fly ash content % by mass of binder	Binder composition: Silica fume content kg/m³	Binder composition: Silica fume content % by mass of binder	Total Binder (kg/m³)	W/CM	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Air %	Compressive Strength (MPa) 1-day, may 2- day	Compressive Strength (MPa) 3-day	Compressive Strength (MPa) 7-day	Compressive Strength (MPa) 14-day	Compressive Strength (MPa) 28-day	Compressive Strength (MPa) 56-day	Compressive Strength (MPa) 91-day,90-day	Flexural Strength (MPa) 7-day	Flexural Strength (MPa) 14-day	Flexural Strength (MPa) 28-day	Flexural Strength (MPa) 56-day	Slump(mm)	E (GPa) 28-day	E (GPa) 56-day
	216	108	30	36	10	360	0.40	144	1138	726		17.5	29.0	36.0		51.0		59.0					10		
	194	144	40	22	6	360	0.40	144	1138	726		15.0	28.0	34.0		51.0		54.0					20		
	230	108	30	22	6	360	0.40	144	1138	726		18.0	31.0	39.0		57.5		60.0					15		
	144	180	50	36	10	360	0.40	144	1138	726		12.0	21.0	27.0		47.0		50.5					15		
	158	180	50	22	6	360	0.40	144	1138	726		10.0	19.0	25.0		44.0		51.0					20		

Appendix B – Chemical and Physical Analysis of Blended Cement and Ordinary Portland Cement

Table B.1 Chemical Analysis of Blended Cement and PortlandCement

Description of Test	Blended Cement	Ordinary Portland Cement (Type 10)
Chemical Analysis,%		
SiO_2	31.2	19.40
Al_2O_3	9.2	5.22
Fe_2O_3	4.9	2.40
CaO	46	61.67
MgO	1.3	2.37
SO_3	2.9	3.86
Alkali	1.0	1.03
Loss of Ignition	2.4	2.47
Potential Compound Composition,%		
C_3S	-	54.07
C_2S	-	14.84
C_3A	-	9.78
C_4AF	-	7.29
Physical Tests		
Blaine	416 m^2/kg	392 m^2/kg
Residue 45 µ	15%	8.37
Autoclave expansion	0.02%	0.08%
Expansion in water	0.02%	0.009%
Setting Time		
Initial	150 min	97 min
Final	255 min	-
Heat of Hydration	292 kJ/kg	-
Compressive Strength		
3-day (> 14.5 MPa)	20.8 MPa	18.76 MPa
7-day(> 20 MPa)	29 MPa	31.02 MPa
28-day(> 26.5 MPa)	43.3 MPa	37.90 MPa

Provided by Holcim (Canada) Inc.

Appendix C –Test Results of All Samples

Table C.1 The Results of 3-7-28-56- and 91- dayCompressive Strength

Run Order	Slump (mm)		Compressive Strength													
			3-day (MPa	3-day (MPa	3-day (MPa	7-day (MPa	7-day (MPa)	7-day (MPa)	28-day (MPa)	28-day (MPa)	28-day (MPa)	56-day (MPa)	56-day (MPa)	56-day (MPa)	91-day (MPa)	91-day (MPa)
1	143.5	146.5	31.80	30.15	31.23	39.58	41.17	41.60	54.89	54.36	55.61	62.69	63.77	64.04	64.17	63.43
2	75.5	76	38.16	38.37	38.73	48.16	49.20	47.38	64.21	66.09	62.50	71.23	71.54	74.93	73.56	76.56
3	22	26	36.64	37.49	36.30	46.60	45.55	47.18	60.50	59.78	59.04	62.77	62.40	61.45	66.38	64.03
4	52	56	32.43	30.49	31.20	40.27	40.33	40.47	56.32	55.26	55.91	58.18	57	59.28	63.2	59.67
5	142	139.5	31.66	33.69	32.84	39.67	41.60	40.22	57.56	57.89	57.20	60.49	61.17	63.02	62.42	62.56
6	71	72.5	34.64	34.80	36.32	41.88	45.99	42.96	62.25	61.38	63.22	67.94	68.74	67.88	68.5	66.46
7	30	30	38.37	35.59	35.86	47.18	45.41	45.71	56.24	58.52	59.89	62.86	65.56	66.14	64.13	65.27
8	47	48.5	34.37	34.17	33.28	41.99	42.86	42.25	55.74	55.91	56.14	62.55	58.51	61.02	64.86	67.82
9	86	86.3	29.77	30.37	31.33	39.37	39.07	39.67	52.87	53.88	52.83	58.08	59.90	57.60	64.76	61.76
10	138	141.5	34.01	36.05	35.25	40.58	42.80	41.37	59.24	59.02	60.15	64.24	63.77	68.68	68.86	67.29
11	51.5	49	34.08	36.08	34.64	46.52	46.18	45.80	60.83	58.90	58.90	62.39	62.89	62.40	65.52	64.91
12	74.5	72	35.38	32.45	34.36	43.69	43.68	43.57	58.89	63.57	57.55	62.98	63.94	56.79	65.68	64.39
13	150	150	25.86	25.15	26.53	34.70	33.32	34.78	49.30	49.50	49.60	51.81	51.70	52.08	57.78	56.67
14	96.5	98	36.13	36.61	35.91	46.47	46.19	46.80	62.84	63.32	60.03	66.74	66.49	68.06	69.23	66.64
15	101	98.5	31.11	32.02	32.20	38.75	37.75	38.41	56.19	55.94	56.38	59.16	59.52	60.04	58.15	61.8
16	71.5	69	33.89	35.44	35.20	45.29	44.78	45.89	61.57	59.55	58.59	65.58	66.30	65.57	69.73	72.19
17	21.5	25	37.51	36.64	37.98	44.79	44.07	46.38	57.81	59.34	60.27	60.71	61.16	60.21	65.97	71.94
18	27	27.5	33.23	34.64	35.12	46.50	45.14	45.40	58.42	59.58	61.52	62.80	64.34	63.99	66.07	69.87
19	77.4	73	30.15	31.12	30.95	37.60	37.50	36.80	58.50	57.77	57.29	62.00	61.20	60.03	64.88	62.57
20	135	135	33.66	33.21	33.04	42.38	44.68	42.22	59.47	59.61	57.82	66.87	59.31	61.03	64.37	65.25

Table C.2 The Results of 3- 7- 28- and 56-day Modulus of Rupture and Modulus of Elasticity

Runs	Modulus of Rupture								Modulus of Elasticity							
	3-day (MPa)	3-day (MPa)	7-day (MPa)	7-day (MPa)	28-day (MPa)	28-day (MPa)	56-day (MPa)	56-day (MPa)	3-day (MPa)	3-day (MPa)	7-day (MPa)	7-day (MPa)	28-day (MPa)	28-day (MPa)	56-day (MPa)	56-day (MPa)
1	3.91	3.82	4.73	4.72	6.25	6.30	6.84	6.75	29.4	29.1	30.7	30.5	33.5	32.7	33.5	33.7
2	4.92	4.91	5.97	5.69	7.47	7.32	7.69	7.66	31.3	30.9	32.2	35.2	35.8	35.2	36.4	36.2
3	4.51	4.67	6.01	6.03	7.27	7.52	7.11	8.20	31.8	31.7	32.6	31.9	33.7	35.8	35.4	36.8
4	4.21	3.98	4.67	5.22	6.34	6.55	7.45	7.10	29.2	28.8	31.8	29.0	32.1	33.1	33.3	35.1
5	3.84	3.81	5.14	4.93	6.57	6.08	6.48	6.86	30.8	30.7	29.3	36.0	32.9	33.5	35.2	33.2
6	4.61	4.61	5.45	5.54	7.01	6.71	7.39	7.73	28.8	28.8	31.1	34.9	34.7	33.9	34.9	34.2
7	5.15	4.89	5.63	5.61	7.30	7.17	7.30	7.34	28.3	29.5	32.7	33.4	35.8	34.9	35.6	36.0
8	4.39	4.19	4.89	5.38	6.91	6.98	7.27	7.09	29.2	30.1	31.7	34.8	33.1	33.3	34.2	35.5
9	3.81	4.02	4.40	4.76	6.46	6.55	6.86	6.93	28.2	27.6	29.4	30.0	32.8	34.1	34.0	34.0
10	4.32	4.29	5.17	5.18	6.87	6.41	6.94	7.04	28.3	28.3	32.1	30.3	34.7	34.6	34.7	33.3
11	4.23	4.02	5.21	5.28	6.92	6.74	7.08	7.04	29.6	29.8	32.7	32.7	33.8	35.7	36.6	35.1
12	4.52	4.65	5.80	5.43	6.91	6.48	7.55	7.38	28.4	30.0	30.4	31.4	34.3	34.4	34.4	35.0
13	3.61	3.38	4.24	4.35	5.88	5.72	6.23	6.30	24.7	25.4	32.4	27.7	33.1	30.8	33.2	30.9
14	4.21	4.47	5.43	5.78	6.77	6.97	7.31	7.33	30.0	29.9	35.1	32.8	34.8	35.5	35.8	36.0
15	4.15	3.91	5.11	4.97	6.54	6.52	6.35	7.28	28.8	28.6	33.4	31.3	33.5	33.9	36.3	34.7
16	4.47	4.57	4.89	5.16	6.53	6.95	7.06	7.46	29.1	28.7	32.5	32.1	33.4	34.9	35.1	34.6
17	4.83	4.96	5.33	4.92	6.90	6.70	7.35	7.38	31.1	29.3	30.6	32.2	34.9	34.3	35.5	35.6
18	4.60	4.89	5.59	5.15	7.15	7.06	7.14	7.49	28.5	31.1	32.0	31.4	34.6	34.6	34.9	34.8
19	4.05	4.32	5.70	5.80	7.17	6.88	7.10	6.97	31.1	32.5	32.1	32.2	34.0	34.0	34.6	36.6
20	4.17	4.08	4.91	4.88	6.71	6.69	6.82	7.20	29.2	27.9	31.4	32.3	33.9	33.3	34.1	34.3

Appendix D – ANOVA Details of Results

Tables D.1 to D.4 display the suggested models, lack of fit test, ANOVA table and summary statistics for the slump test.

Table D.1 Sequential Model Sum of Squares of Slump

Source	Sum of Squares	Degree of Freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	138278.5	1	138278.5			
Linear vs. Mean	27906.44	4	6976.61	12.95	< 0.0001	Suggested
Quadratic vs. Linear	6390.017	10	639.00	1.89	0.2490	
Sp Cubic vs. Quadratic	1468.09	3	489.36	4.48	0.1875	Aliased
Residual	218	2	109			

Table D.2 Lack of Fit Ttests of Slump

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Linear	7858.107	13	604.47	5.55	0.1629	Suggested
Quadratic	1468.09	3	489.36	4.49	0.1875	
Special Cubic	0	0				Aliased
Pure Error	218	2	109			

Table D.3 Analysis of Variance Table of Slump

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	27906.44	4	6976.61	12.95	< 0.0001	significant
Linear Mixture	27906.44	4	6976.61	12.95	< 0.0001	
Residual	8076.10	15	538.40			
Lack of Fit	7858.10	13	604.46	5.545	0.1629	not significant
Pure Error	218	2	109			
Cor Total	35982.55	19				

Table D.4 Model Summary Statistics for Slump

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	23.20	0.78	0.71	0.62	13516.7	Suggested
Quadratic	18.36	0.95	0.82	-5.33	227826.7	
Special Cubic	10.44	0.99	0.94		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for the slump are shown in the following figures.

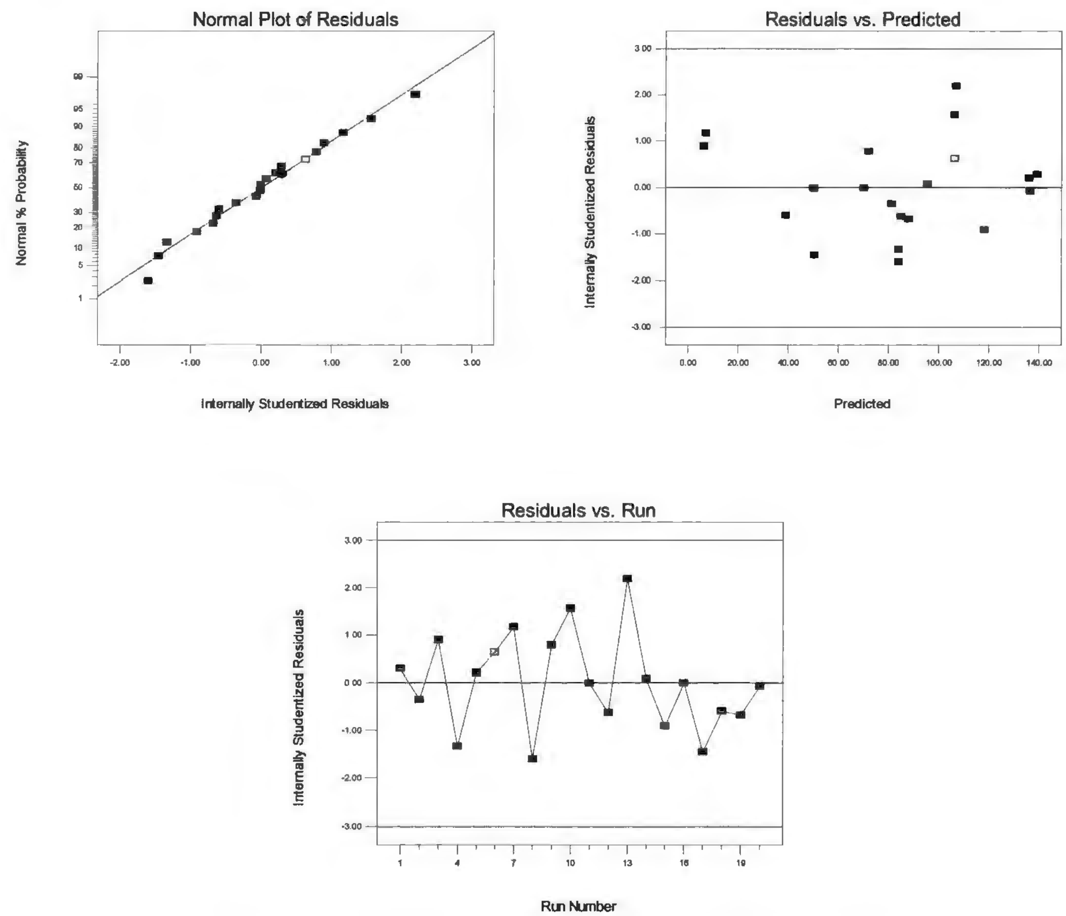


Figure D.1 Plots of ANOVA Assumptions for Slump

Tables D.5 to D.8 display the suggested models, lack of fit test, ANOVA table and summary statistics for 3-day compressive strength.

Table D.5 Sequential Model Sum of Squares for 3-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs Total	22792.05	1	22792.05			
Linear vs Mean	147.98	4	36.99	29.71	< 0.0001	Suggested
Quadratic vs Linear	14.97	10	1.49	2.02	0.2268	
Sp Cubic vs Quadratic	0.39	3	0.13	0.080	0.9653	Aliased
Residual	3.31	2	1.65			

Table D.6 Lack of Fit Ttests for 3-day Compressive Strength

Source	Sum of Squares		Mean Square	F- Value	p-value Prob> F	
Linear	15.36	13	1.18	0.71	0.7190	Suggested
Quadratic	0.39	3	0.13	0.079	0.9653	
Special Cubic	0	0				Aliased
Pure Error	3.31	2	1.65			

Table D.7 Analysis of Variance Ttable for 3-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	147.98	4	36.99	29.71	< 0.0001	significant
Linear Mixture	147.98	4	36.99	29.71	< 0.0001	
Residual	18.67	15	1.24			
Lack of Fit	15.36	13	1.181	0.713	0.7190	not significant
Pure Error	3.31	2	1.65			
Cor Total	166.6	19				

Table D.8 Model Summary Statistics for 3-day Compressive Strength

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	1.12	0.89	0.86	0.80	33.51	Suggested
Quadratic	0.86	0.98	0.92	0.80	33.66	
Special Cubic	1.29	0.98	0.81		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 3-day compressive strength are shown in the following figures.

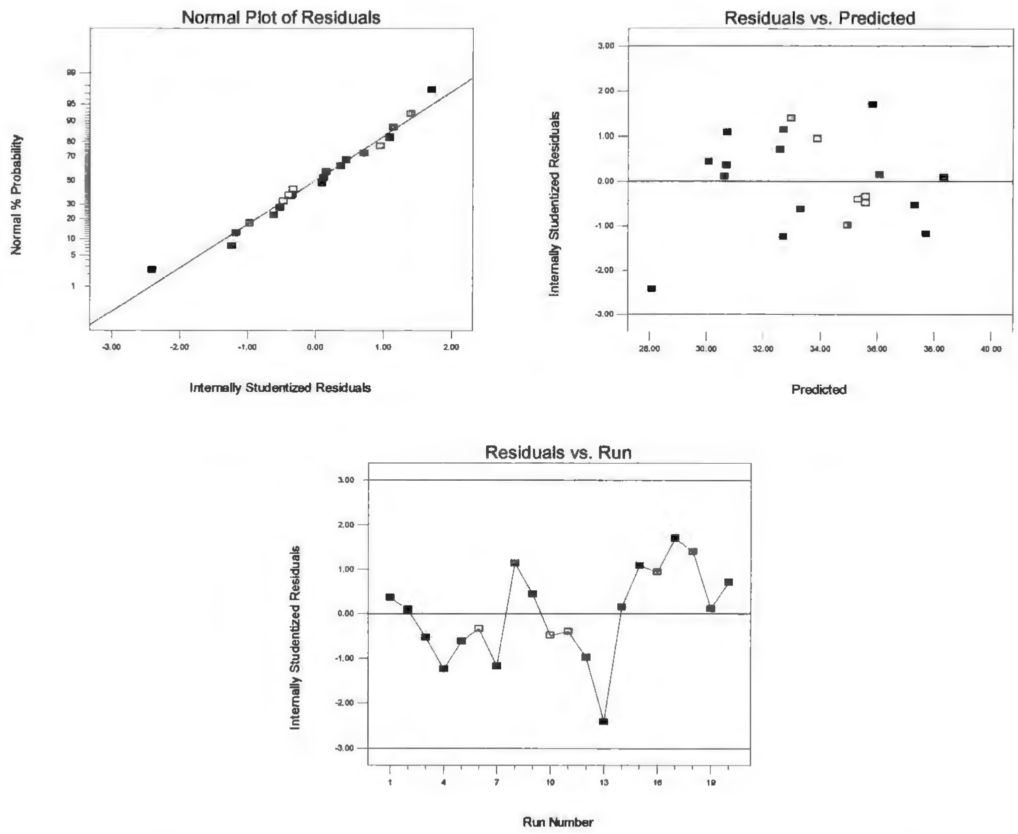


Figure D.2 Plots of ANOVA Assumptions for 3-day Compressive Strength

Tables D.9 to D.12 display the suggested models, lack of fit test, ANOVA table and summary statistics for 7-day compressive strength.

Table D.9 Sequential Model Sum of Squares for 7-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	36529.02	1	36529.02			
Linear vs. Mean	201.11	4	50.28	14.95	< 0.0001	Suggested
Quadratic vs. Linear	36.17	10	3.62	1.26	0.4192	
Sp Cubic vs. Quadratic	10.19	3	3.39	1.66	0.3967	Aliased
Residual	4.08	2	2.04			

Table D.10 Lack of Fit Tests for 7-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Linear	46.36	13	3.56	1.74	0.4221	Suggested
Quadratic	10.18	3	3.39	1.66	0.3967	
Special Cubic	0	0				Aliased
Pure Error	4.08	2	2.04			

Table D.12 Analysis of Variance Table for 7-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	201.11	4	50.27	14.95	< 0.0001	significant
Linear Mixture	201.11	4	50.27	14.95	< 0.0001	
Residual	50.43	15	3.362			
Lack of Fit	46.35	13	3.56	1.74	0.4221	not significant
Pure Error	4.08	2	2.04			
Cor Total	251.55	19				

Table D.12 Model Summary Statistics for 7-day Compressive Strength

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	1.83	0.80	0.74	0.65	86.58	Suggested
Quadratic	1.68	0.94	0.78	-1.84	714.57	
Special Cubic	1.42	0.98	0.84		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 7-day compressive strength are shown in the following figures.

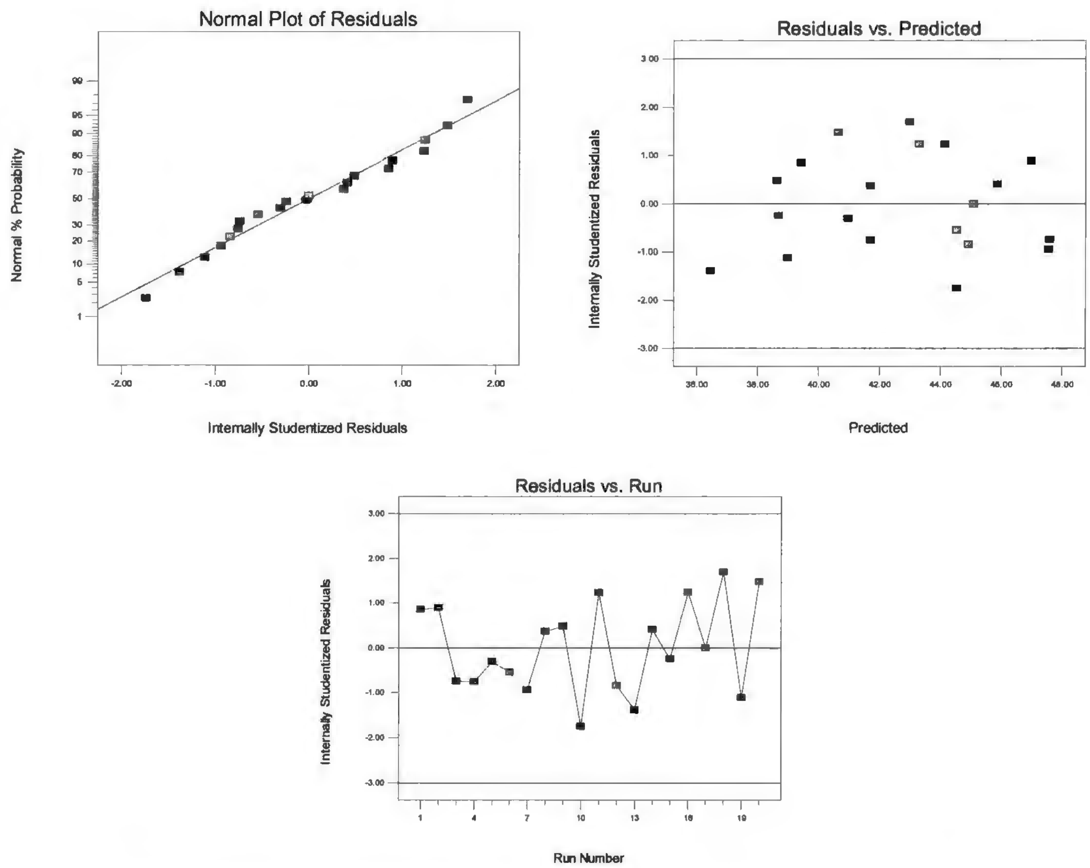


Figure D.3 Plots of ANOVA Assumptions for 7-day Compressive Strength

Tables D.13 to D.16 display the suggested models, lack of fit test, ANOVA table and summary statistics for 56-day compressive strength.

Table D.13 Sequential Model Sum of Squares for 56-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	78356.42	1	78356.42			
Linear vs. Mean	257.48	4	64.37	10.35	0.0003	Suggested
Quadratic vs. Linear	84.49	10	8.44	4.82	0.0481	Suggested
Sp Cubic vs. Quadratic	2.03	3	0.67	0.20	0.8874	Aliased
Residual	6.70	2	3.35			

Table D.14 Lack of Fit Tests for 56-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Linear	86.53	13	6.66	1.98	0.3846	Suggested
Quadratic	2.04	3	0.68	0.20	0.8874	Suggested
Special Cubic	0	0				Aliased
Pure Error	6.71	2	3.35			

Table D.15 Analysis of Variance Table for 56-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	257.48	4	64.37	10.35	0.0003	significant
Linear Mixture	257.48	4	64.37	10.35	0.0003	
Residual	93.24	15	6.21			
Lack of Fit	86.53	13	6.65	1.98	0.3846	not significant
Pure Error	6.70	2	3.35			
Cor Total	350.72	19				

Table D.16 Model Summary Statistics for 56-day Compressive Strength

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	2.49	0.73	0.66	0.49	176.63	Suggested
Quadratic	1.32	0.97	0.90	0.01	346.87	Suggested
Special Cubic	1.83	0.98	0.82		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 56-day compressive strength are shown in the following figures.

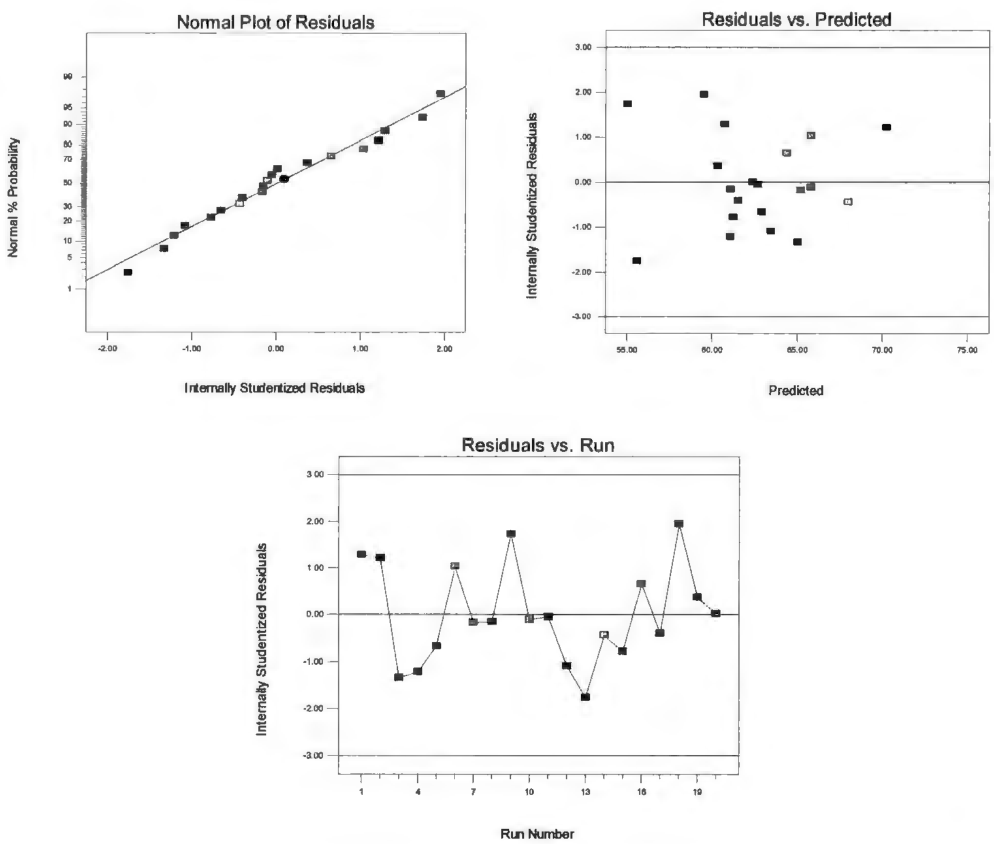


Figure D.4 Plots of ANOVA Assumptions for 56-day Compressive Strength

Tables D.17 to D.20 display the suggested models, lack of fit test, ANOVA table and summary statistics for 91-day compressive strength.

Table D.17 Sequential Model Sum of Squares for 91-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	85765.7	1	85765.7			
Linear vs. Mean	154.80	4	38.70	4.18	0.0179	
Quadratic vs. Linear	122.72	10	12.27	3.85	0.0748	Suggested
Sp. Cubic vs. Quadratic	3.74	3	1.24	0.20	0.8862	Aliased
Residual	12.18	2	6.09			

Table D.18 Lack of Fit Tests for 91-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Linear	126.46	13	9.73	1.59	0.45	
Quadratic	3.74	3	1.25	0.20	0.88	Suggested
Special Cubic	0	0				Aliased
Pure Error	12.18	2	6.09			

Table D.19 Analysis of Variance Table for 91-day Compressive Strength

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	236.25	6	39.37	8.95	0.0005	significant
Linear Mixture	154.80	4	38.70034	8.79	0.0012	
AC	33.55	1	33.55	7.62	0.0162	
BE	63.68	1	63.68	14.47	0.0022	
Residual	57.19	13	4.39			
Lack of Fit	45.00	11	4.09	0.67	0.7323	not significant
Pure Error	12.18	2	6.0925			
Cor Total	293.44	19				

Table D.20 Model Summary Statistics for 91-day Compressive Strength

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	3.04	0.53	0.40	0.06	274.59	
Quadratic	1.78	0.94	0.79	0.41	171.51	Suggested
Special Cubic	2.468	0.96	0.60		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 91-day compressive strength are shown in the following figures.

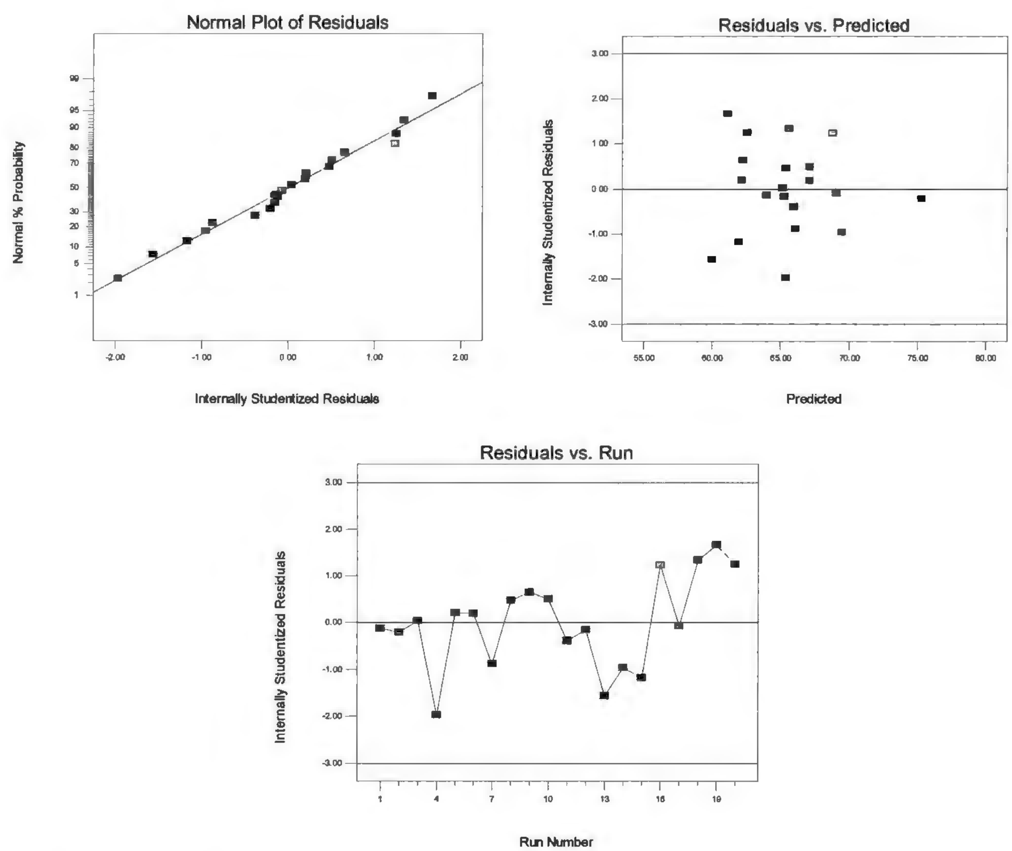


Figure D.5 Plots of ANOVA Assumptions for 91-day Compressive Strength

Tables D.21 to D.24 display the suggested models, lack of fit test, ANOVA table and summary statistics for 3-day Modulus of rupture.

Table D.21 Sequential Model Sum of Squares for 3-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	373.42	1	373.42			
Linear vs. Mean	2.34	4	0.58	10.87	0.0002	Suggested
Quadratic vs. Linear	0.61	10	0.06	1.49	0.3443	
Sp. Cubic vs. Quadratic	0.13	3	0.04	1.32	0.4581	Aliased
Residual	0.07	2	0.03			

Table D.22 Lack of Fit tests for 3-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Linear	0.74	13	0.05	1.67	0.4350	Suggested
Quadratic	0.13	3	0.04	1.32	0.4581	
Special Cubic	0	0				Aliased
Pure Error	0.06	2	0.03			

Table D.23 Analysis of Variance Table for 3-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	2.34	4	0.58	10.87	0.0002	significant
Linear Mixture	2.34	4	0.58	10.87	0.0002	
Residual	0.80	15	0.05			
Lack of Fit	0.74	13	0.0	1.67	0.4350	not significant
Pure Error	0.06	2	0.03			
Cor Total	3.15	19				

Table D.24 Model Summary Statistics for 3-day Modulus of Rupture

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.23	0.74	0.67	0.51	1.54	Suggested
Quadratic	0.20	0.93	0.75	-2.15	9.95	
Special Cubic	0.18	0.97	0.79		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 3-day flexural strength are shown in the following

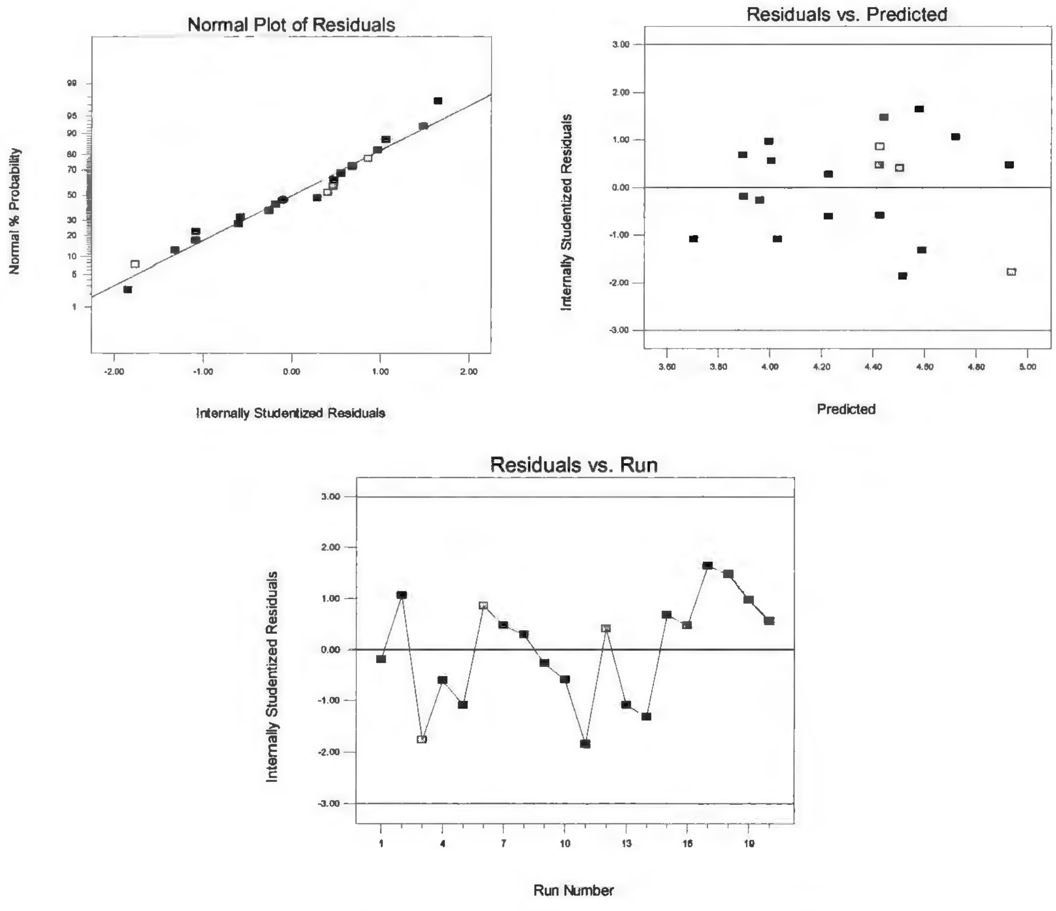


Figure D.6 Plots of ANOVA Assumptions for 3-day Modulus of Rupture

Tables D.25 to D.28 display the suggested models, lack of fit test, ANOVA table and summary statistics for 7-day Modulus of rupture.

Table D.25 Sequential Model Sum of Squares for 7-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	542.25	1	542.25			
Linear vs. Mean	2.69	4	0.67	13.80	< 0.0001	Suggested
Quadratic vs. Linear	0.51	10	0.05	1.20	0.4430	
Sp. Cubic vs. Quadratic	0.14	3	0.04	1.40	0.4423	Aliased
Residual	0.06	2	0.03			

Table D.26 Lack of Fit tests for 7-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Linear	0.66	13	0.05	1.47	0.4755	Suggested
Quadratic	0.14	3	0.05	1.40	0.4423	
Special Cubic	0	0				Aliased
Pure Error	0.06	2	0.03			

Table D.27 Analysis of Variance Table for 7-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	2.69	4	0.67	13.80	< 0.0001	significant
Linear Mixture	2.69	4	0.67	13.80	< 0.0001	
Residual	0.73	15	0.048			
Lack of Fit	0.66	13	0.051	1.47	0.4755	not significant
Pure Error	0.069	2	0.034			
Cor Total	3.43042	19				

Table D.28 Model Summary Statistics for 7-day Modulus of Rupture

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.22	0.78	0.73	0.60	1.370328	Suggested
Quadratic	0.21	0.93	0.76	-6.36	25.27593	
Special Cubic	0.18	0.97	0.81		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 7-day flexural strength are shown in the following figures.

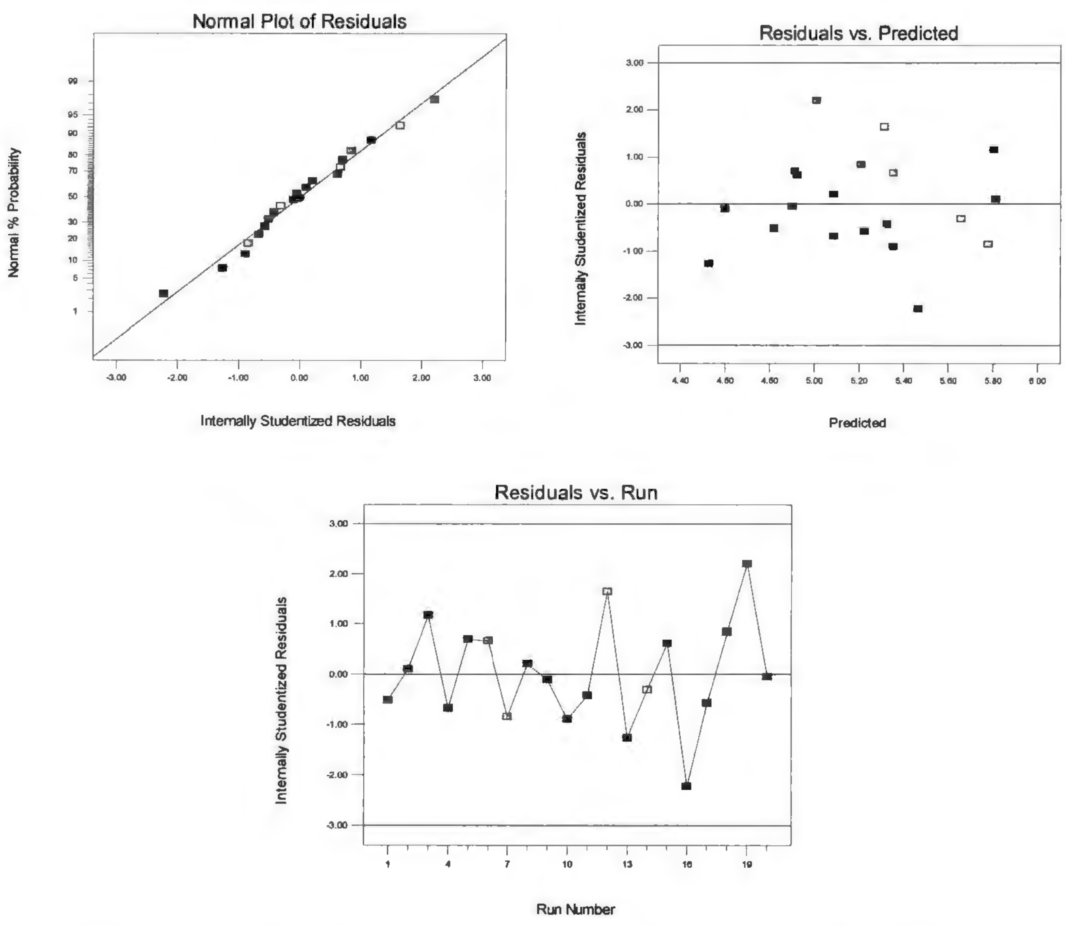


Figure D.7 Plots of ANOVA Assumptions for 7-day Modulus of Rupture

Tables D.29 to D.32 display the suggested models, lack of fit test, ANOVA table and summary statistics for 28-day Modulus of rupture.

Table D.29 Sequential model Sum of Squares for 28-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	915.03	1	915.03			
Linear vs. Mean	1.89	4	0.47	11.15	0.0002	Suggested
Quadratic vs. Linear	0.32	10	0.03	0.51	0.8269	
Sp. Cubic vs. Quadratic	0.16	3	0.05	0.78	0.6031	Aliased
Residual	0.14	2	0.07			

Table D.30 Lack of Fit Tests for 28-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Linear	0.49	13	0.037	0.52	0.8122	Suggested
Quadratic	0.16	3	0.05	0.78	0.6031	
Special Cubic	0	0				Aliased
Pure Error	0.14	2	0.07			

Table D.31 Analysis of Variance Table for 28-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F Value	p-value Prob> F	
Model	1.89	4	0.47	11.15	0.0002	significant
Linear Mixture	1.89	4	0.47	11.15	0.0002	
Residual	0.63	15	0.042			
Lack of Fit	0.49	13	0.037	0.52	0.8122	not significant
Pure Error	0.14	2	0.072			
Cor Total	2.52	19				

Table A.32 Model Summary Statistics for 28-day Modulus of Rupture

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.20	0.74	0.68	0.57	1.09	Suggested
Quadratic	0.25	0.87	0.53	-9.84	27.40	
Special Cubic	0.26	0.94	0.45		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 28-day flexural strength are shown in the following figures.

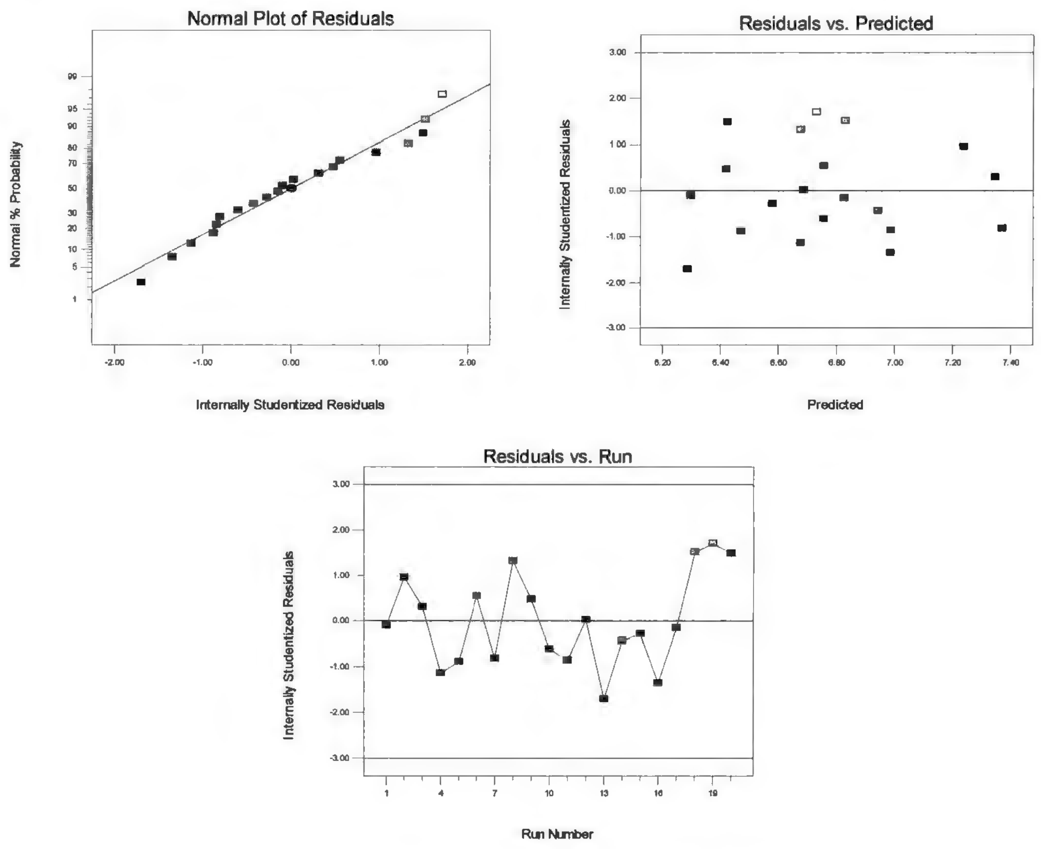


Figure D.8 Plots of ANOVA Assumptions for 28-day Modulus of Rupture

Tables D.33 to D.36 display the suggested models, lack of fit test, ANOVA table and summary statistics for 56-day Modulus of rupture.

Table D.33 Sequential Model Sum of Squares for 56-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Mean vs. Total	1022.73	1	1022.73			
Linear vs. Mean	1.54	4	0.38	10.46	0.0003	Suggested
Quadratic vs. Linear	0.32	10	0.032	0.70	0.7021	
Sp.Cubic vs. Quadratic	0.06	3	0.02	0.28	0.8373	Aliased
Residual	0.16	2	0.08			

Table D.34 Lack of Fit Tests for 56-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F- Value	p-value Prob> F	
Linear	0.39	13	0.03	0.37	0.8933	Suggested
Quadratic	0.068	3	0.02	0.28	0.8373	
Special Cubic	0	0				Aliased
Pure Error	0.16	2	0.08			

Table D.35 Analysis of Variance Table for 56-day Modulus of Rupture

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	1.54	4	0.38	10.458	0.0003	significant
Linear Mixture	1.540	4	0.385	10.458	0.0003	
Residual	0.55	15	0.036			
Lack of Fit	0.39	13	0.030	0.374	0.8933	not significant
Pure Error	0.16	2	0.080			
Cor Total	2.092	19				

Table D.36 Model Summary Statistics for 56-day Modulus of Rupture

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.19	0.73	0.66	0.52	0.99	Suggested
Quadratic	0.21	0.89	0.58	-4.52	11.54	
Special Cubic	0.28	0.92	0.26		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 56-day flexural strength are shown in the following figures.

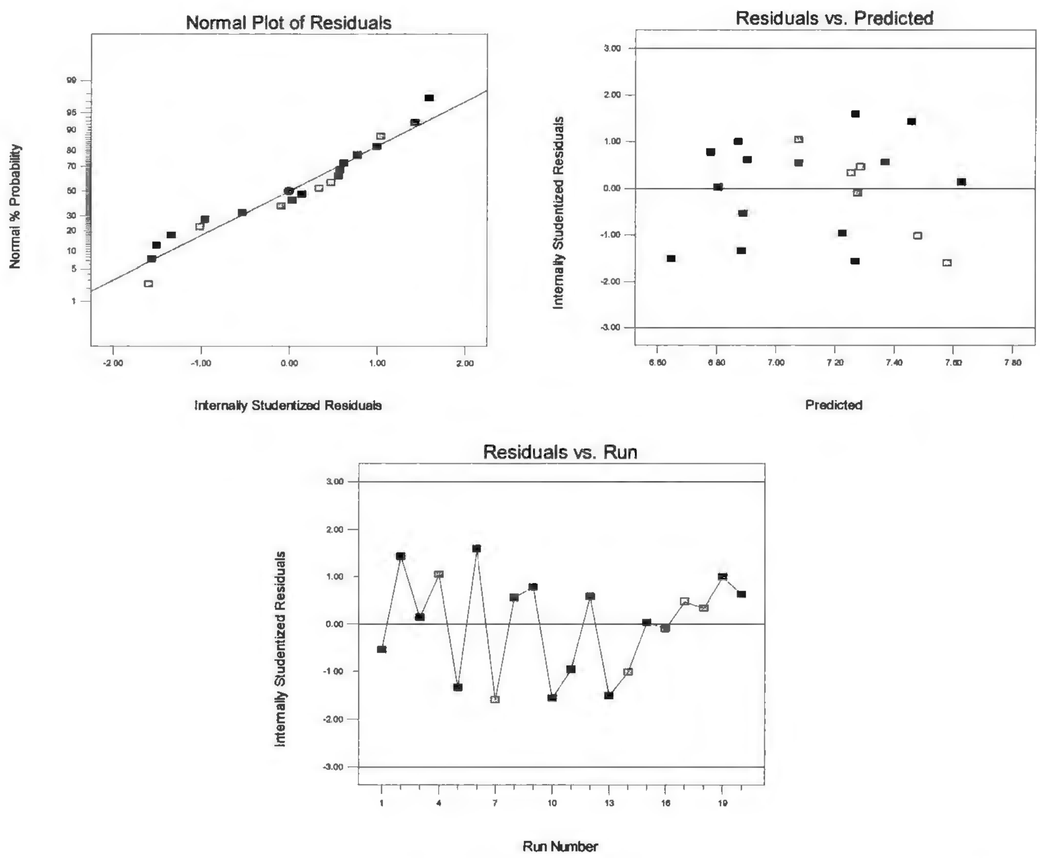


Figure D.9 Plots of ANOVA Assumptions for 56-day Modulus of Rupture

Tables D.37 to D.40 display the suggested models, lack of fit test, ANOVA table and summary statistics for 3-day Modulus of elasticity.

Table D.37 Sequential Model Sum of Squares for 3-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Mean vs. Total	17242.54	1	17242.54			Suggested
Linear vs. Mean	13.09	4	3.27	1.73	0.1955	Suggested
Quadratic vs. Linear	13.64	10	1.36	0.46	0.8591	
Sp. Cubic vs. Quadratic	14.33	3	4.77	25.35	0.0382	Aliased
Residual	0.37	2	0.18			

Table D.38 Lack of Fit Tests for 3-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Linear	27.98	13	2.15	11.42	0.0833	Suggested
Quadratic	14.33	3	4.77	25.35	0.0382	
Special Cubic	0	0				Aliased
Pure Error	0.37	2	0.18			

Table D.39 Analysis of Variance Table for 3-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	13.09	4	3.27	1.73	0.1955	not significant
Linear Mixture	13.092	4	3.273	1.731	0.1955	
Residual	28.357	15	1.89			
Lack of Fit	27.980	13	2.15	11.425	0.0833	not significant
Pure Error	0.3769	2	0.18845			
Cor Total	41.449	19				

Table D.40 Model Summary Statistics for 3-day Modulus of Elasticity

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	1.37	0.31	0.13	-0.32	54.76	Suggested
Quadratic	1.715	0.64	-0.34	-57.81	2438.03	
Special Cubic	0.434	0.99	0.91		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

Tables D.41 to D.44 display the suggested models, lack of fit test, ANOVA table and summary statistics for 7-day Modulus of elasticity.

Table D.41 Sequential Model Sum of Squares for 7-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Mean vs. Total	20421.16	1	20421.16			
Linear vs. Mean	17.83	4	4.458	7.14	0.0020	Suggested
Quadratic vs. Linear	3.10	10	0.31	0.24	0.9712	
Sp. Cubic vs. Quadratic	0.77	3	0.25	0.09	0.9562	Aliased
Residual	5.48	2	2.74			

Table D 42 Lack of Fit Tests for 7-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Linear	3.87	13	0.29	0.11	0.9967	Suggested
Quadratic	0.77	3	0.25	0.09	0.9562	
Special Cubic	0	0				Aliased
Pure Error	5.48	2	2.74			

Table D.43 Model Summary Statistics for 7-day Modulus of Elasticity

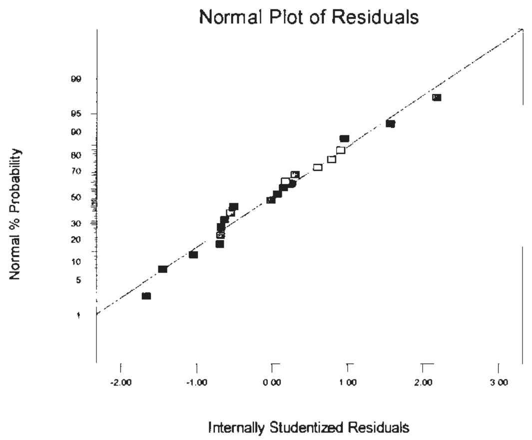
Source	Standard Deviation	R-Squared	R-Squared Adjusted	Predicted R-Squared	PRESS	
Linear	0.790058	0.655737	0.563934	0.466249	14.51636	Suggested
Quadratic	1.119149	0.769736	0.124995	-1.81164	76.46793	
Special Cubic	1.655929	0.798352	-0.91566		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

Table D.44 Analysis of Variance Table for 7-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	18.13	4	4.532	7.356	0.0017	significant
Linear Mixture	18.13	4	4.53	7.35	0.0017	
Residual	9.242	15	0.616			
Lack of Fit	3.758	13	0.289	0.105	0.9971	not significant
Pure Error	5.484	2	2.74			
Cor Total	27.37	19				

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 7-day modulus of elasticity are shown in the following figures.



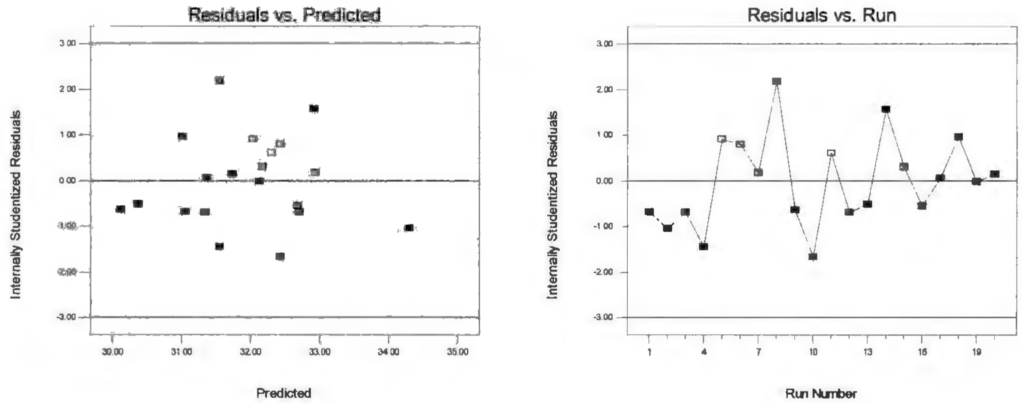


Figure D.10 Plots of ANOVA Assumptions for 7-day Modulus of Elasticity

Tables D.45 to D.48 display the suggested models, lack of fit test, ANOVA table and summary statistics for 28-day Modulus of elasticity.

Table D.45 Sequential Model Sum of Squares for 28-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Mean vs. Total	23183.28	1	23183.28			
Linear vs. Mean	12.60	4	3.15	11.85	0.0002	Suggested
Quadratic vs. Linear	3.375	10	0.33	2.75	0.1377	
Sp Cubic vs. Quadratic	0.37	3	0.12	1.033	0.5262	Aliased
Residual	0.24	2	0.12			

Table D.46 Lack of Fit Tests for 28-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Linear	3.74	13	0.28	2.39	0.3325	Suggested
Quadratic	0.37	3	0.12	1.03	0.5262	
Special Cubic	0	0				Aliased
Pure Error	0.24	2	0.12			

Table D.47 Analysis of Variance Ttable for 28-day Modulus of Elasticity

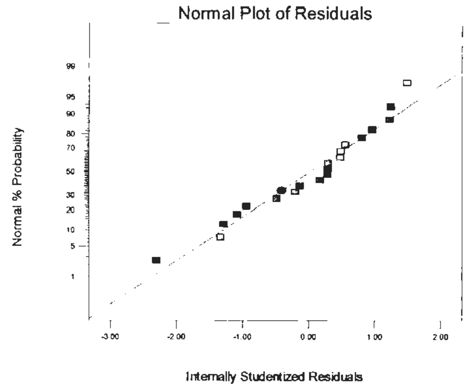
Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	12.60	4	3.15	11.85	0.0002	significant
Linear Mixture	12.604	4	3.151	11.85	0.0002	
Residual	3.98	15	0.265			
Lack of Fit	3.748	13	0.288	2.39	0.3325	not significant
Pure Error	0.24	2	0.120			
Cor Total	16.59	19				

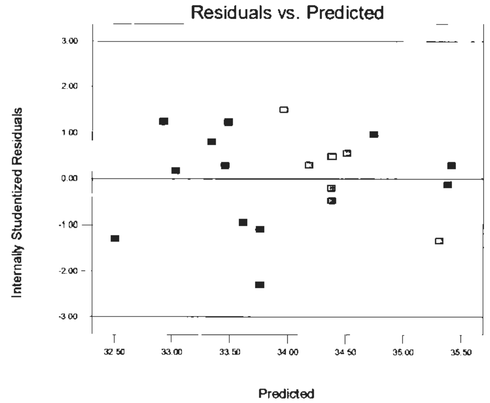
Table D.48 Model Summary Statistics for 28-day Modulus of Elasticity

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.51	0.75	0.69	0.61	6.52	Suggested
Quadratic	0.35	0.96	0.85	-1.53	42.08	
Special Cubic	0.346	0.98	0.86		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 28-day modulus of elasticity are shown in the following figures.





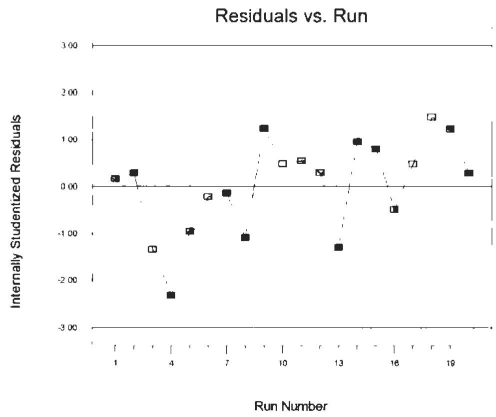


Figure D.11 Plots of ANOVA Assumptions for 28-day Modulus of Elasticity

Tables D.49 to D.52 display the suggested models, lack of fit test, ANOVA table and summary statistics for 56-day Modulus of elasticity.

Table D.49 Sequential Model Sum of Squares for 56-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Mean vs. Total	24328.8	1	24328.8			
Linear vs. Mean	11.76	4	2.94	9.64	0.0005	Suggested
Quadratic vs. Linear	3.54	10	0.35	1.70	0.2883	
Sp Cubic vs. Quadratic	0.67	3	0.22	1.26	0.4695	Aliased
Residual	0.35	2	0.17			

Table D.50 Lack of Fit Tests for 56-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Linear	4.22	13	0.32	1.81	0.4102	Suggested
Quadratic	0.67	3	0.22	1.26	0.4695	
Special Cubic	0	0				Aliased
Pure Error	0.35	2	0.17			

The normality plot of residuals (normality assumption), plot of residuals vs. predicted values (constant variance assumption), and the plot of residuals vs. run orders (independence assumption) for 56-day modulus of elasticity are shown in the following figures.

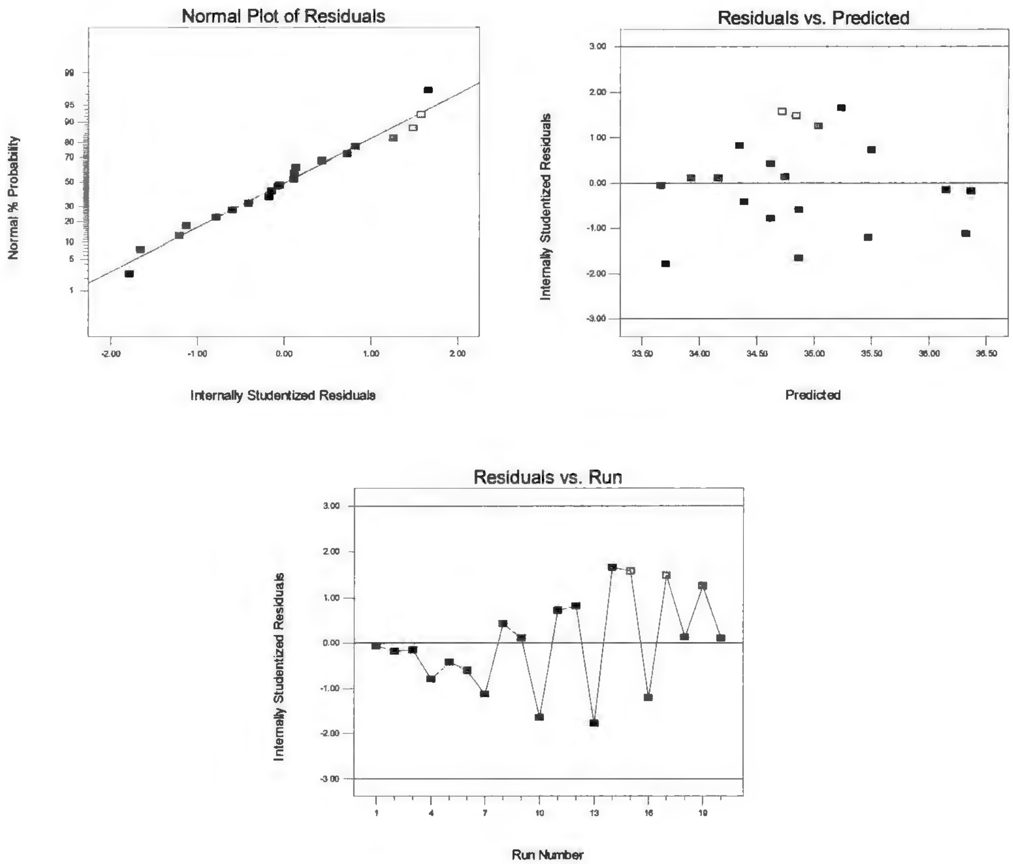


Figure D.12 Plots of ANOVA Assumptions for 56-day Modulus of Elasticity

Table D.51 Model Summary Statistics for 56-day Modulus of Elasticity

Source	Standard Deviation	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.55	0.72	0.64	0.48	8.44	Suggested
Quadratic	0.45	0.93	0.75	-5.76	110.59	
Special Cubic	0.42	0.97	0.79		+	Aliased

+ : Case(s) with leverage of 1.0000, PRESS statistic not defined

Table D.52 Analysis of Variance Table for 56-day Modulus of Elasticity

Source	Sum of Squares	Degree of freedom	Mean Square	F-Value	p-value Prob> F	
Model	11.76	4	2.942	9.643	0.0005	significant
Linear Mixture	11.768	4	2.942	9.643	0.0005	
Residual	4.576	15	0.305			
Lack of Fit	4.219	13	0.324	1.817	0.4102	not significant
Pure Error	0.357	2	0.178			
Cor Total	16.34418	19				