MULTI-RESPONSE OPTIMIZATION OF CONCRETE MANUFACTURING PROCESS PARAMETERS: DESIRABILITY FUNCTION APPROACH

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Approval of the Graduate School

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I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

MULTI-RESPONSE OPTIMIZATION OF CONCRETE MANUFACTURING PROCESS PARAMETERS: DESIRABILITY FUNCTION APPROACH

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Because construction companies have a lot of dynamics and fierce competition environment, proficiency of improving the quality of construction and making the building stronger are the main goals to become forefront at the market and get strategically right position.

After carrying out experiments, compressive strength of concrete should be maximized to make strong building to avoid building from collapse. The water absorption of concrete should be minimized to reduce the risks of destruction of buildings. The flow of concrete should also be maximized to be used conveniently without an extra effort. It is believed that this will help for the quality of construction if all the responses are simultaneously optimized.

Keywords: Design of experiment, concrete, compressive strength, flow table, water absorption, ANOVA, multi-response optimization, desirability function approach.

ÖZET

BETON ÜRETİM SÜRECİ PARAMETRELERİNİN ÇOK CEVAPLI OPTİMİZASYONU: ÇEKİCİLİK FONKSİYONU YAKLAŞIMI

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İnşaat şirketlerinin çok fazla dinamiğe ve şiddetli rekabet ortamına sahip olmasından dolayı, inşaat kalitesini artırmak ve binayı güçlendirebilmek, pazarda ön plana çıkmanın ve stratejik olarak doğru konumda olmanın temel amaçlarıdır.

Binanın çökmesini önlemek ve güçlü bir yapı oluşturmak için deneyler yapılmalı ve betonun basınç dayanımı enbüyüklenmelidir. Binaların tahrip olma riskini azaltmak için betonun su emme oranı en aza indirilmelidir. Ayrıca beton akışı, fazladan çaba sarf etmeden rahatça kullanılabilecek şekilde enbüyüklenmelidir. Tüm cevapların eş zamanlı eniyilenmesi durumunda, bunun inşaatın kalitesine yardımcı olacağına inanılmaktadır.

Anahtar Kelimeler: Deney tasarımı, beton, basınç dayanımı, akış tablosu, su soğurumu, varyans analizi, çok-yanıtlı eniyileme, çekicilik fonksiyonu yaklaşımı.

To my grand father

Acknowledgments

I express my sincere appreciation to Professor Dr. Ahmet Sermet Anagün for his assistance, advice, and kindness.

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CHAPER 1: INTRODUCTION

Construction companies has become the most important contributions to economics of any country. The demand for construction sector continues to increase day by day. The demand for construction companies continue to increase because of increase of the population of the world and the buildings get older over time.

It is requested that the concrete should be very strong enough to meet the standard quality for the construction companies. For this purpose, the concrete quality characteristics indicators such as compressive strength, water absorption rate, flow table, ultrasound and bending strength tests are done. Concretes were prepared by mixing the water, cement, aggregate and admixture amounts according to the design matrix designed with experimental design method. These samples were tested 7 and 28 days. In addition, all experimental results for compressive strength, flexural strength, water absorption and flow table of concrete were tried to be found and analyzed using Minitab to find out which one is better.

Producing good and quality of product for construction are very important in order to defeat other construction companies. Concrete with weak compressive strength is one of the main challenging factors while dealing with construction companies.

In this study, three responses namely flow table, water absorption, and compressive strength are being considered during the experimental process. In order to prepare the mixes at the laboratory, four ingredients commonly mentioned in the related literature used; cement, water, aggregate, and admixture. On the other hand, two different solution approaches applied; responses optimized both individually and simultaneously. During simultaneous optimization of the responses, desirability function approach is utilized. The reason why multiple response optimization is performed is that in real application, we might find one good setting for one response but might be worse for other responses.

Addition, in contrast to Plackett-Burman design or fractional factorial design, full factorial design preferred in order to determine not only the significant main effects, but also two or higher levels of interaction effects. Another feature of the study may be curing time used before conducting the tests. Two different curing time are performed which are 7 days and 28 days, and a comparison between those two curing time is carried out.

This study is composed of seven chapters. The first chapter is the introduction of thesis which explains the objective of the thesis. The second chapter introduces some information about concrete, advantages and disadvantages of concrete usage, and the ingredients of concrete mixes. The definition of design of experiment (DoE), implementation of DoE, types of DoE are discussed in the following chapter. The fourth chapter is about literature research. The next chapter explains the experimental procedure including the ingredients used, preparation of the mixture, molding, and tests performed. Chapter six discusses the analyzing procedure applied for the data obtained after performing the test. Firstly, an individual optimization for each response (i.e. flow table, water absorption, and compressive strength) is applied. Then, multi-response optimization is employed. The last chapter summarizes the results of the analyses and gives suggestions to other people who will perform the similar studies or experiments for the future.

CHAPTER 2: WHAT IS CONCRETE?

Concrete is a composite material, which is made from a mixture of cement, aggregate (sand or gravel, etc.), water and sometimes chemical or mineral admixtures in required proportions. It is one of the most important and useful materials for construction work (URL-1).

Once all the ingredients are mixed with proper proportions, the concrete hardens in mass due to the interaction between cement and water. When aggregates and admixtures are added, the performance of the concrete improves.

In concrete technology, a variety of type-names has been used for different types of concrete. This classification is based on three factors (URL-2):

1. Type of material used in its making.
2. Nature of stress conditions.
3. And it’s density.

2.1 The Ingredients of Concrete

Even though the strength and other properties of concrete depend on the type of materials used, the ingredients of concrete generally consist of cement, aggregates, water, and admixture, if necessary.

Cement is used as a binding material. This material binds aggregate particles together. Because it is economical and strong enough for ordinary construction, lime is preferred as binding material instead of cement.

Since many parameters relating to the composition of the individual cement minerals and their proportions in the cement can affect the rate of strength growth and the final strength achieved, the selection of cement or the quality of cement is an important issue for concrete making process (URL-4).

Excessive amount of cement use is harmful for (URL-12):

1. It will not be economically viable for the project
2. Excessive cement means high heat of hydration which lead to thermal stresses in concrete which will lead to cracks in concrete.
3. Cement in excess quantity means excess cementitious paste. Shrinkage in concrete is directly proportional to the amount of paste in concrete. So there will many shrinkage cracks in concrete if due precautions are not taken.
4. Excessive cement does not guarantee you excess strength

Aggregates fills all open spaces in between the coarse particles, and decreases the porosity of the final mass. Sand, grain size is about 2 mm, is commonly and universally used as a fine aggregate.

Aggregates strongly influence concrete's freshly mixed and hardened properties, mixture proportions, and economy. Consequently, selection of aggregates is an important process.

Although some variation in aggregate properties is expected, characteristics that are considered include (URL-5):

- grading
- durability
- particle shape and surface texture
- abrasion and skid resistance
- unit weights and voids
- absorption and surface moisture

Since water plays an important role in the process of the chemical reaction of cement and aggregates, it is the main component of the concrete mix.

Determining the correct amount of water is very crucial for preparing the concrete mix. When water/cement ratio is not properly set, some performance characteristics may be affected, such as decreasing compressive strength, increasing corrosion, lack of thawing.

In addition to improper amount of water use, presence of impurities in water for concrete mix leads to decrease in structural properties of concrete such as strength and durability to a large extent (URL-7).

Anything other than cement, aggregates, and water if added in concrete either before or during mixing to alter the properties to our desired requirement are termed as admixtures (URL-8).

Chemical admixtures, influences the drying or setting time of cement, are classed as optional ingredients, and used for specific reasons.

The major reasons for using admixtures are (URL-9):

- To reduce the cost of concrete construction
- To achieve certain properties in concrete more effectively than by other means
- To maintain the quality of concrete during the stages of mixing, transporting, placing, and curing in adverse weather conditions
- To overcome certain emergencies during concreting operations.

2.2 Advantages and Disadvantages of Concrete

Among all the construction materials used in the world, concrete is most widely used due to its unique advantages compared to other materials. The major advantages of concrete are given below (URL-10):

- Concrete is economical (raw materials can be found everywhere)

- Concrete hardens at ambient temperature
- Ability to be cast into any shape
- Energy efficiency in production
- Excellent water resistance characteristics
- High-temperature resistance
- Ability to consume and recycle waste
- Application in reinforced concrete
- Low or zero maintenance required
- Multi-mode application

Despite the numerous advantages, concrete has certain disadvantages as follow (URL-11):

- Compared to other binding materials, the tensile strength of concrete is relatively low.
- Concrete is less ductile than construction steel.
- The weight of compared is high compared to its strength. Concrete may contain soluble salts. Soluble salts cause efflorescence.

CHAPTER 3: DESIGN OF EXPERIMENTS

The design of experiments (DoE) is the process of planning experiments so that appropriate data will be collected, the minimum number of experiments will be performed to acquire the necessary technical information, and suitable statistical methods will be used to analyze the collected data (Park, 2003). DoE is an approach used in numerous industries for conducting experiments to develop new products and processes faster, and to improve existing products and processes. When applied correctly, it can decrease time to market, decrease development and production costs, and improve quality and reliability (Treglia, 2015).

3.1 Classical Design of Experiments (OFAT)

Montgomery (2013) suggests that three types of experimentation strategies exist: Best Guess, One-Factor-At-a-Time (OFAT) and Statistical Designed Experiments (DoE). The first one consists of using prior knowledge to modify several variables and conduct the experiment under conditions expected to give the best results.

Secondly, OFAT strategy consists of modifying one variable at a time while keeping the others fixed. Finally, DoE is the most effective method for solving complex problem with many variables.

In OFAT experiments, one factor or variable is varied until its best setting is found, while the others kept fixed. It is then fixed at this level. Next, the other factor is then changed until its best setting is found and held constant at this setting. The whole process is repeated with another factor. In addition to the number of experiments required increase, one of the important disadvantages of OFAT is that it does not have the ability to discover the presence of interaction between the factors of the process. However, statistically designed experiments that vary several factors simultaneously are more efficient when studying two or more factors.

On the other hand, based on Czitrom's study (1999), DoE presents the following advantages over OFAT:

- It requires less resources (experiments, time, material, etc.) for the amount of information obtained
- The estimates of the effect of each factors (variable) on the response are more precise
- The interactions between factors can be estimated systematically (Interactions are not estimable with OFAT experiments)
- There is experimental information in a larger region of the factor space.

The use of DoE is most beneficial in multidisciplinary application, where traditional engineering analysis, simulation and verification are difficult to achieve. DoE uses statistical experimental methods to develop the best factor and level settings to optimize a process or a design (Wahid and Nadir, 2013).

3.2 Statistical Design of Experiments

In general, the DoE starts with "statement of the experimental problem" and ends "confirmation test", "recommendation to management", and "planning of additional experiments", if necessary. The outline of experimental design procedure is depicted in Figure 1.

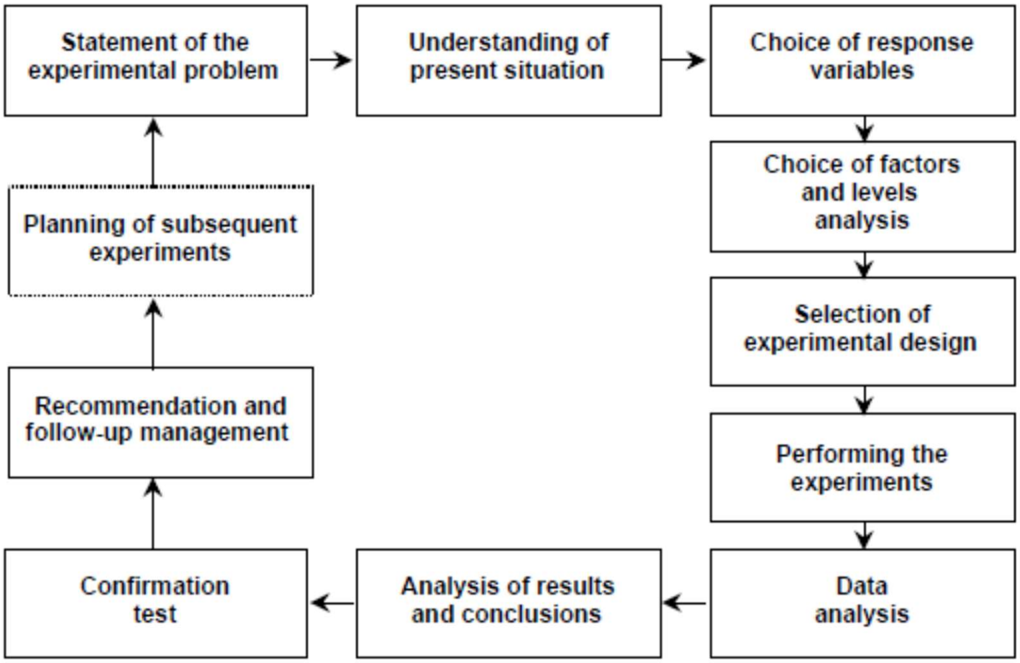

Figure 1 The outline of experimental procedure (Park, 2003)

Statement of the experimental problem is somehow important step, because it helps understanding of the current situation, and possible outcomes after the experiments. Then, the responses and factors affecting the responses need to be determined. The responses, often called dependent variables, are variables being measured during the experiment. On the other hand, factors, often called independent variables, are variables being manipulated in the experiment. Factors may be related to gender and work experience for workers, temperature and humidity for manufacturing environment, stirring rate and feed rate for machine, number of additives and properties for material.

Once the number of factors is selected, number of levels for each factor needs to be determined. Since the levels of the factors directly affect the number of experiments that need to be done, an attention should be paid while determining the levels of the factors. The levels of factors may be in binary form such as gender variable (i.e. Male or Female, two-level factor), in real form such as feed rate for a machine (i.e. 12 mm/min, 16 mm/min, 20 mm/min and 24 mm/min, four-level factor). In other words, the levels of the factors do not have to be equal.

The experimental design being conducted may be selected by taking into account for the number of factors, the number of levels of each factors, the interaction effects among factors are of interest, time and budget constraints. For example, if there are more than five factors, each has two-level, screening design (i.e. Plackett-Burman design) may be an appropriate one. On the other hand, if the number of factors is about five, regardless of the levels, factorial design (either full or fractional factorial design, depending upon the time and budget constraints) could be selected. If the number of factors are less than five and the levels of each factor are more than two, response surface methodology may be applied for optimization purpose.

The experiments are performed by means of selected experimental design structure. A randomized, controlled trial is considered the most reliable and impartial method of gathering necessary data. It is insufficient to obtain one observation for each experiment.

It is important to carry out the experiments with at least two replicates in random manner. The obtained data is analyzed via analysis of variance (ANOVA). Appropriate factor levels of significant factors and interactions may simply be chosen by evaluating the main and interaction effects plots in accordance with the direction of improvement (i.e. minimizing the unit weight of a product or maximizing the compressive strength of a material).

Based on the results obtained from analysis stage, confirmation tests may be planned. These tests are crucial especially to verify the consistency of the results for the following stages of manufacturing. If the results of the confirmation tests and the estimation values determined after the data analysis are compatible, it is said that the problem is solved and some recommendations may be made to help the employees and organizations to solve similar problems.

3.3 Types of Design of Experiments

There are many different types of DoE. They may be classified as follows according to the allocation of factor combinations and the degree of randomization of experiments (Park, 2003):

1. **Factorial design**: This is a design for investigating all possible treatment combinations which are formed from the factors under consideration. The order in which possible treatment combinations are selected is completely random. Single-factor, two-factor and three-factor factorial designs belong to this class, as do 2^k (k factors at two levels) and 3^k (k factors at three levels) factorial designs.

2. **Fractional factorial design**: This is a design for investigating a fraction of all possible treatment combinations which are formed from the factors under investigation. This type of design is used when the cost of the experiment is high and the experiment is time-consuming.

3. **Randomized complete block design, split-plot design and nested design**: All possible treatment combinations are tested in these designs, but some form of restriction is imposed on randomization. For instance, a design in which each block contains all possible treatments, and the only randomization of treatments is within the blocks, is called the randomized complete block design.

4. **Incomplete block design**: If every treatment is not present in every block in a randomized complete block design, it is an incomplete block design. This design is used when we may not be able to run all the treatments in each block because of a shortage of experimental apparatus or inadequate facilities.

5. **Response surface design and mixture design**: This is a design where the objective is to explore a regression model to find a functional relationship between the response variable and the factors involved, and to find the optimal conditions of the factors. Central

composite designs, rotatable designs, simplex designs, mixture designs and evolutionary operation (EVOP) designs belong to this class. Mixture designs are used for experiments in which the various components are mixed in proportions constrained to sum to unity.

6. **Robust design**: Taguchi (1986) developed the foundations of robust design, which are often called parameter design and tolerance design. The concept of robust design is used to find a set of conditions for design variables which are robust to noise, and to achieve the smallest variation in a product's function about a desired target value. Tables of orthogonal arrays are extensively used for robust design.

CHAPTER 4: LITERATURE RESEARCH

In the study of Şimşek et. al (2013), a full factorial design is applied for multi response optimization via desirability function approach. Two response variables, namely slump flow rate and compressive strength for ready mix concrete. They used four factors each has two levels: Water to binder materials ratio, Coarse aggregate (II) to total aggregate ratio, Superplasticizer content, and fly ash amount. Two responses are optimized based on the desirability function approach using response optimizer, a feature of Minitab software, the optimal levels of factors are verified according to the confirmation runs.

Huang and Shen (2011) used statistical tools such as descriptive statistics, full factorial design and analysis of source of variation to identify the potential factors that impact the validity of testing method for determining the strength of cement. A 2^4 full factorial design is selected, each factor has two levels. They found that the strength significantly varied between 3 and 28 days.

Zahraee et. al (2013) tried to combines design of experiments and simulation for determining the best combination of resources for a real construction process, namely concrete pouring process. In the study, four two-level factors are selected and full factorial design with center points implemented. They successfully developed a model for predicting concrete pouring process productivity and determined optimum resources levels.

Priyadarshana and Dissanayake (2013) investigate the importance of consistent cement quality for sustainable construction. They selected 5 brands of cement from the market, compare the strength of mortars for different length of time. Samples were secured every month from January 2011 to October 2011. These samples are tested for mortar strength at 1day, 2day, 7day and 28day, chemical composition, fineness, consistency (initial & final setting time), water demand and soundness. Test specimens, prepared as 40mm X 40mm X 160mm prismatic pieces according to EN 196 -1 standard, are cast from batch of plastic mortar containing one part by mass of cement and three parts by mass of standard sand with a water/cement ratio of 0.5.

In the study of Saikaew (2009), the optimal operating conditions of the significant process factors influencing compressive strength and number of voids in the concrete fence product are determined. A simultaneous optimization of multi-response variables carried out a tool called "desirability" coupled with optimization algorithms of response surface methodology (RSM) to achieve a specific target for the mean compressive strength and minimum voids based on predictive models.

Cihan et. al (2013) proposed a two-stage experimental procedure, fractional factorial design and D-optimal design. For the fractional factorial design application, seven factors each with two levels are investigated based on 2^{7-3} design. For the D-Optimal design, two aggregate sizes are considered such as 11.2 and 22.4 mm. The compressive strength is selected as response variable.

In the study of Mosaberpanah and Eren (2016) the relationship between the 28-days compressive strength and the compression toughness factor is investigated There are five factors are considered and forty-five batches are conducted to obtain a model. They found a linear model representing the relation between the responses with R^2 value of 0.7082.

Ayan et. al (2011) exemplified parameter optimization of compressive strength of steel fiber reinforced high strength concrete by statistical design and analysis of experiments. Five parameters that affecting the compressive strength examined such as age of testing, binder type, binder amount, curing type and steel fiber volume fraction. Taguchi analysis techniques have been used to evaluate $L_{27}(3^{13})$ Taguchi’s orthogonal array experiments. It is stated that the maximum compressive strength has been observed as around 124 MPa based on the optimal parameter level combination. It is also clearly shown that all main parameters except steel fiber significantly contribute to the compressive strength of steel fiber reinforced high strength concrete, while age and binder type are the most significant contributors.

In the study of Correia et al. (2010) the potential use of waste vulcanized rubber scrap particles as aggregate in construction mortars is investigated. The experiments are conducted based on 3^2 factorial design of experiments, i.e. two factors each has three levels, and the response surface methodology In order to prepare mortar mixes, WRS as fine aggregate and water/cement ratios are considered. Two response, namely fresh mortar consistency index and hardened mortar 28-day compressive strength, are evaluated.

Mukharjee and Barai (2014) investigated the influence of water/cement ratio and addition of Nano-Silica as partial replacement of cement on two responses, the compressive strength and water absorption of mortar mixes. A 3^2 factorial design is used to determine the effect of rge selected factors. The compressive strengths of mixes are measured for 3, 7, and 28 days, while the water absorption is for 28 days only. It is observed from ANOVA, the main factors have significant effects on both responses.

Alqadi et. al (2013) examined changes in compressive strength of self-compacting concrete with a 2^k factorial design. Four factors each has two levels are selected: cement content, water to powder ratio, fly ash content, and superplasticizer. Based on the results obtained from the analysis, two and higher order interactions are found to be significant. The maximum compressive strength of self-compacting concrete is obtained for the setting of all factors to their high levels.

Chang et. al (2011) applied weighted Gray-Taguchi method to optimize recycle aggregate concrete mixtures. The control factors used are; water/cement ratio, volume ratio of recycled coarse aggregate, replacement by river sand, content of crushed brick, and cleanliness of aggregate. The experiments are conducted to optimize four responses namely; slump, slump-flow, resistivity (7-day, 14-day, 28-day), ultrasonic pulse velocity (7-day, 14-day, 28-day), and compressive strength (7-day, 14-day, 28-day). Based on the results obtained from multiple response optimization via Gray-Taguchi method and confirmation runs, the optimal combination in terms of levels of the factors is determined as A1B1C1D2E1.

Ozbay et. al (2009) investigated the optimal mix proportion parameters of high strength self- compacting concrete for fresh and harden states by taken into consideration of six factors, each has 3 levels, via L_{18} Taguchi orthogonal array. Six different responses are taken into account for the study such as ultrasonic pulse velocity (UPV), compressive strength, splitting tensile strength, air content, water permeability, and water absorption. It is stated that ultrasonic pulse velocity (UPV), compressive strength, splitting tensile strength are being increased based on the optimal levels for mix proportions, the remaining responses decreased.

Asadzadeh and Khoshbayan (2018) applied Box-Behnken approach to find significant factors affect the production process of foam concrete. Cement, water, and foam are used to make concrete mixes. Three responses are considered as dry density, compressive strength in 28 days, and cost. Dry density and cost should be minimized, while the compressive strength maximized. A total of 15 mixes are prepared according to the design matrix. The optimal levels of the factors are investigated for the values of density within different intervals via desirability function.

When the given literature is evaluated, it is seen that full factorial design is preferred in the majority of studies. The number of factors considered in the studies is between three and six. The curing time for the concrete pieces was usually 28 days. Mostly, single response variable was considered. In multi-response studies, single-response optimizations were performed instead of multiple optimization. On the other hand, there are very few studies using the desirability function approach to optimize multi-response simultaneously.

In the light of these explanations, the simultaneous optimization of three response variables with the desirability function approach under the influence of two different curing time (i.e. 7 and 28 days) and four factors, namely cement, water, aggregate, and admixture, may be considered as a contribution to the related literature.

CHAPTER 5: EXPERIMENTAL PROCEDURE

The experiments are conducted at Izmir University of Economics Civil Engineering laboratory. During the experiments, sixteen different mixes of concrete are prepared and flow table tests, water absorption tests, and compressive strength tests are performed.

Based on the literature, results of preliminary tests and laboratory limitations in terms of equipment and materials, four factors, namely cement, aggregate, water, and admixture, are selected and the experiments are planned considering these factors. In order to examine not only main effects of the factors, but also all interaction effects among factors at all orders, full factorial design is selected. The experiments being conducted are determined considering each factor has 2 levels. The selected levels for the factors, and the design matrix (2^4=16 experiments, meaning there are four factors each has two levels) are given in Table 1 and Table 2, respectively.

Table 1 The selected levels of factors

Factors	**Low level**	**High level**
Cement	X	1.5X
Aggregate	2.5X	3X
Water	0.5X	0.55X
Admixture	0X	0.005X

In the experiments; cement, aggregate, water, and admixture are used to prepare mixes according to the ratios given in design matrix.

In order to prepare the mixes based on the design matrix, commercially available cement is used as binder (the minimum compressive strength of this cement obtained at 28 days under the specific mixture and testing conditions specified shows the characteristic properties of this cement). The name of the cement used is BATIÇİM PORTLAND ÇİMENTO TS EN 197-1 CEM I 42,5 R, and the name of the aggregate used is LIMAK BATI ÇIMENTO CEN STANDARD KUMU TS EN 196-1.

Table 2 Design matrix for the experiments

Cement	Aggregate	Water	Admixture
X	3X	0.5X	0X
X	3X	0.5X	0.005X
X	3X	0.55X	0X
X	3X	0.55X	0.005X
X	2.5X	0.5X	0X
X	2.5X	0.5X	0.005X
X	2.5X	0.55X	0X
X	2.5X	0.55X	0.005X
1.5X	3X	0.5X	0X
1.5X	3X	0.5X	0.005X
1.5X	3X	0.55X	0X
1.5X	3X	0.55X	0.005X
1.5X	2.5X	0.5X	0X
1.5X	2.5X	0.5X	0.005X
1.5X	2.5X	0.55X	0X
1.5X	2.5X	0.55X	0.005X

Cement mortar is made by mixing cement and aggregate according to the ratio between cement and aggregate (the mass of aggregate should be half as the mass of cement). The mixer used for this process is depicted in Figure 2.

Figure 2 Mixer used for mixing the materials

After mixing cement and aggregate, certain amount of water is added in accordance with ratio given in design matrix. Once everything is mixed for five minutes, mixed material is taken outside of mixer and put into mold. The molds used in the experiments are given in Figure 3.

Figure 3 Molds used to make concrete pieces

As seen in Figure 3, each mold has three channels with dimension of 40x40x160 mm. Since two molds are filled by the mixes, six pieces of samples are obtained to be used for testing stage. The mixes are kept in the molds for one day. After casting, all sample pieces are compacted by rodding. Then, they are then molded out and transferred to the curing water tank at 23±2 ˚C until testing, as in Figure 4.

Figure 4 Water tank for concrete pieces

5.1 The Tests Performed

Implementation of the tests performed are explained in the following subsections.

5.1.1 Flow table test

After preparing the mixes, the flow table test is done. Mixture is placed to frusto-conical mold with placed three layers (as seen in Figure 5). Each layer is rodded 15 times and then sample is dropped 25 times. Afterwards, the spreading diameter of the samples are measured three times and the average is calculated (see Figure 6). The value of flow table test is desired to be maximized as possible. The data of flow table test are given in Appendix 1.

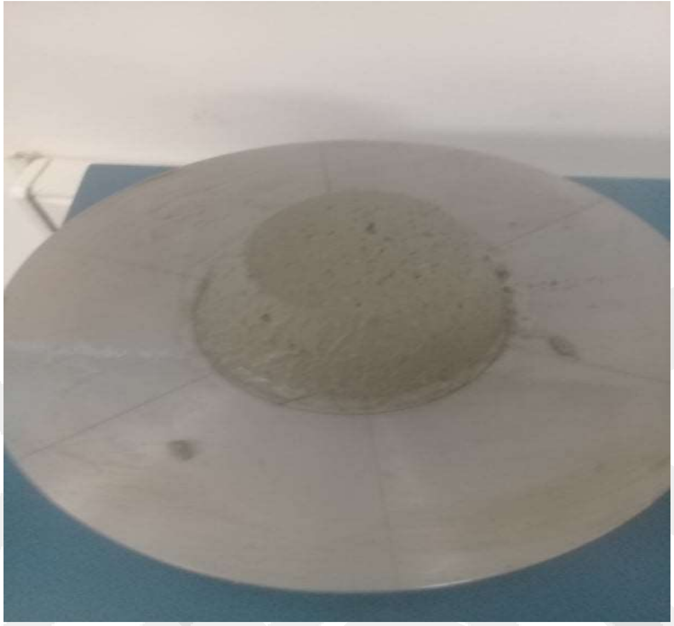

Figure 5 The sample is ready for testing of table flow

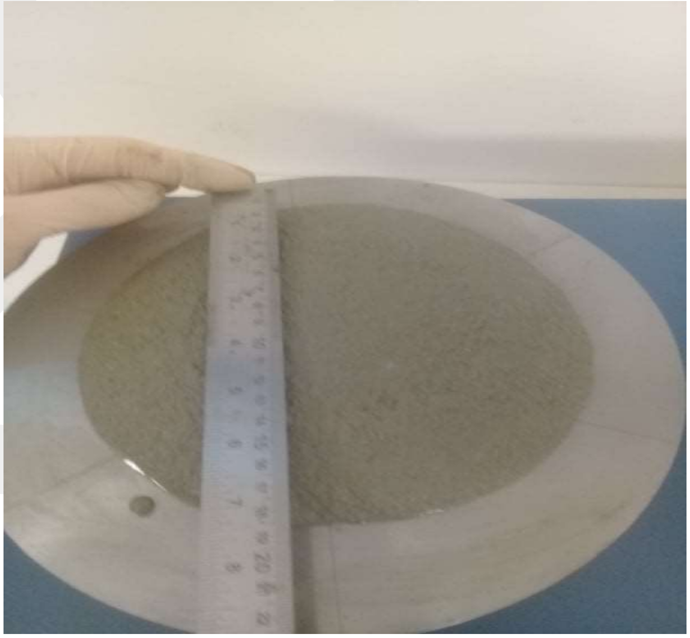

Figure 6 Measuring the spreading diameter of the sample

The flow is the resulting increase in average base diameter of the mortar mass, measured on at least four diameters at approximately equal-spaced intervals (layers) expressed as a percentage of the original base diameter (URL-13)

$$\text{Flow} = [(D_{avg} - D_o) / D_o]*100$$

where, D_{avg} is and average base diameter, and D_o is the original base diameter.

5.1.2 Water absorption test

Absorption can be described as the ability to take water by means of capillary suction. Water absorption consists of preconditioning cylindrical samples to a known moisture content. Then exposing the bottom surface of the sample to liquid water and measuring the increase in mass resulting from water absorption (Castro, et. al, 2011).

The samples kept in water tank for a limited time (i.e. 7 and/or 28 days) are taken outside and weighed as saturated surface dry condition. Then they are put into oven at 100 °C for 24 hours and their dry weights are measured. Water absorption capacities for all concrete pieces are calculated by using the following equation:

$$\text{Water Absorption Capacity} = \frac{(\text{Wet Weight} - \text{Dry Weight})}{\text{Dry Weight}} * 100$$

The value of water absorption test is desired to be minimized as possible. The data of water absorption test are given in Appendix 1.

5.1.3 Compressive strength test

The compressive strength is measured by breaking concrete specimens in a compression-testing machine. The compressive strength is calculated from the failure load divided by the cross-sectional area (Morel, et. al, 2005).

Compressive strength test is conducted using a compression test machine. The concrete specimens are placed inside of the test machine. As seen Figure 7, the machine gives compressive strength values for each concrete specimen in the unit of kN.

Figure 7 The machine for testing compressive strength value for concrete piece

The readings obtained for the compressive strength test are then used to calculate the average for each experiment given in the design matrix. The value of compressive strength test is desired to be maximized as possible. The data of compressive strength test are given in Appendix 1.

CHAPTER 6: ANALYSES OF EXPERIMENTS

All of the analyses are performed using Minitab Software (www.minitab.com). For each analysis, firstly, analysis of variance (ANOVA) table is created, then a reduced model is obtained by removing insignificant factors and/or interactions according to p-values. Finally, a built-in module available for the selected software, named as "response optimizer", is applied to optimize the response as well as determine the proper levels of factors. This methodology is separately applied for each response (i.e. flow table, water absorption, and compressive strength) for 7 days and 28 days curing times, respectively. Then, simultaneous optimization process is run for the data obtained from each curing time. The results are given in the following subsections.

6.1 Analyzing Data for Flow Table Response

Based on the data obtained from the experiments for flow table response, the ANOVA table created is given in Table 3.

Table 3 ANOVA for flow table response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	217.869	15.562	11.27	0.230
Linear	4	199.883	49.971	36.19	0.124
Cement	1	149.451	149.451	108.25	0.061
Aggregate	1	13.876	13.876	10.05	0.195
Water	1	17.851	17.851	12.93	0.173
Admixture	1	18.706	18.706	13.55	0.169
2-Way Interactions	6	10.894	1.816	1.32	0.583
Cement*Aggregate	1	0.076	0.076	0.05	0.854
Cement*Water	1	5.176	5.176	3.75	0.304
Cement*Admixture	1	1.381	1.381	1.00	0.500
Aggregate*Water	1	1.501	1.501	1.09	0.487
Aggregate*Admixture	1	1.381	1.381	1.00	0.500
Water*Admixture	1	1.381	1.381	1.00	0.500
3-Way Interactions	4	7.093	1.773	1.28	0.573
Cement*Aggregate*Water	1	2.976	2.976	2.16	0.381
Cement*Aggregate*Admixture	1	0.106	0.106	0.08	0.828
Cement*Water*Admixture	1	3.331	3.331	2.41	0.364
Aggregate*Water*Admixture	1	0.681	0.681	0.49	0.610
Error	1	1.381	1.381		
Total	15	219.249			

As seen in the last column of Table 3, none of the factors and/or interactions are significant because p-values are greater than 0.05. In order to determine a reduced model, the factors or interactions with higher p-values are being removed from the original model one by one or procedures available within Minitab Software may be applied. Since the first approach is very time consuming, the procedures, namely forward selection, stepwise, and backward elimination, are mostly preferred when the number of factors and/or interactions is more. Hence, a backward elimination procedure is applied, and the reduced model for FT is given in Table 4.

Table 4 ANOVA for reduced model for flow table response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	5	205.058	41.012	28.90	0.000
Linear	4	199.882	49.971	35.21	0.000
Cement	1	149.451	149.451	105.31	0.000
Aggregate	1	13.876	13.876	9.78	0.011
Water	1	17.851	17.851	12.58	0.005
Admixture	1	18.706	18.706	13.18	0.005
2-Way Interactions	1	5.176	5.176	3.65	0.085
Cement*Water	1	5.176	5.176	3.65	0.085
Error	10	14.191	1.419		
Total	15	219.249			

As observed in Table 4, four main effects are significant, and cement is the most significant factor among all others ($p<0.000$). Cement*Water interaction is also considered significant ($p<0.10$). The regression equation for flow table (FT) response including significant factors and interactions is obtained as:

$$\begin{aligned} FT \;=\;& 16{,}806 - 3.056\,\text{Cement} - 0.931\,\text{Aggregate} + 1.056\,\text{Water} + 1.081\,\text{Admixture} \\ & + 0.569\,\text{Cement*Water} \end{aligned}$$

These analyses also show that 93.53% of the variation of FT may be explained by the factors and interaction appeared in the model (meaning R-sq=93.53%). The adjusted R-sq is calculated as 90.29%, and standard error of estimation is 1.1913. These values validate that the reduced model may be used for prediction of FT response.

In order to optimize FT response itself, a response optimizer is run, and optimal setting for levels of the factors proposed by such module as follows:

Variable	Setting
Cement	-1
Aggregate	-1
Water	1
Admixture	1

Response	Fit	SE Fit	95% CI	95% PI
FT	22.362	0.730	(20.737; 23.988)	(19.250; 25.475)

The results show that the value of FT response would be observed as 22.362 on average, standard error of estimation 0.73 when Cement and Aggregate are set to low levels, Water and Admixture to high levels. The results also show that, if the setting of the factors are kept as is, the value of FT response would be within 20.737 and 23.988 with 95% confidence interval (CI), 19.250 and 25.475 with 95% prediction interval (PI).

6.2 Analyzing Data for Water Absorption Response

The initial ANOVA table for water absorption (WA) data is obtained using Minitab Software, and given in Table 5.

Based on the Table 5, it can be said that all main effects are significant as well as almost two-level and three-level interactions, except Cement*Aggregate*Water interaction (p=0.950>0.05). The backward elimination approach may be applied to finalize the model being used for prediction of WA. The reduced model for WA is given in Table 6.

Table 5 ANOVA for water absorption response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	79.8718	5.7051	174.50	0.059
Linear	4	39.0419	9.7605	298.54	0.043
Cement	1	25.7797	25.7797	788.50	0.023
Aggregate	1	2.3062	2.3062	70.54	0.075
Water	1	1.9494	1.9494	59.62	0.082
Admixture	1	9.0066	9.0066	275.48	0.038
2-Way Interactions	6	27.0944	4.5157	138.12	0.065
Cement*Aggregate	1	0.1867	0.1867	5.71	0.252
Cement*Water	1	0.6237	0.6237	19.08	0.143
Cement*Admixture	1	12.5171	12.5171	382.85	0.033
Aggregate*Water	1	1.0778	1.0778	32.97	0.110
Aggregate*Admixture	1	0.3272	0.3272	10.01	0.195
Water*Admixture	1	12.3619	12.3619	378.10	0.033
3-Way Interactions	4	13.7355	3.4339	105.03	0.073
Cement*Aggregate*Water	1	0.0002	0.0002	0.01	0.950
Cement*Aggregate*Admixture	1	1.7295	1.7295	52.90	0.087
Cement*Water*Admixture	1	11.1665	11.1665	341.54	0.034
Aggregate*Water*Admixture	1	0.8394	0.8394	25.67	0.124
Error	1	0.0327	0.0327		
Total	15	79.9045			

As seen in Table 6, all main effects and most of the interaction effects are significant ($p<0.05$) as well as Cement*Aggregate interaction ($p=0.078<0.10$) where the confidence interval is set to 90%. The regression equation for WA response including significant factors and interactions is obtained as:

$$\begin{aligned} WA = \; & 7{,}4822 - 1{,}2693\,\text{Cement} - 0{,}3797\,\text{Aggregate} + 0{,}3490\,\text{Water} \\ & - 0{,}7503\,\text{Admixture} - 0{,}1080\,\text{Cement*Aggregate} + 0{,}1974\,\text{Cement*Water} \\ & - 0{,}8845\,\text{Cement*Admixture} - 0{,}2595\,\text{Aggregate*Water} \\ & + 0{,}1430\,\text{Aggregate*Admixture} + 0{,}8790\,\text{Water*Admixture} \\ & + 0{,}3288\,\text{Cement*Aggregate*Admixture} + 0{,}8354\,\text{Cement*Water*Admixture} \\ & - 0{,}2290\,\text{Aggregate*Water*Admixture} \end{aligned}$$

Table 6 ANOVA for reduced model of water absorption response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	13	79.8716	6.1440	373.55	0.003
Linear	4	39.0419	9.7605	593.44	0.002
Cement	1	25.7797	25.7797	1567.40	0.001
Aggregate	1	2.3062	2.3062	140.22	0.007
Water	1	1.9494	1.9494	118.52	0.008
Admixture	1	9.0066	9.0066	547.60	0.002
2-Way Interactions	6	27.0944	4.5157	274.56	0.004
Cement*Aggregate	1	0.1867	0.1867	11.35	0.078
Cement*Water	1	0.6237	0.6237	37.92	0.025
Cement*Admixture	1	12.5171	12.5171	761.04	0.001
Aggregate*Water	1	1.0778	1.0778	65.53	0.015
Aggregate*Admixture	1	0.3272	0.3272	19.89	0.047
Water*Admixture	1	12.3619	12.3619	751.60	0.001
3-Way Interactions	3	13.7353	4.5784	278.37	0.004
Cement*Aggregate*Admixture	1	1.7295	1.7295	105.15	0.009
Cement*Water*Admixture	1	11.1665	11.1665	678.92	0.001
Aggregate*Water*Admixture	1	0.8394	0.8394	51.03	0.019
Error	2	0.0329	0.0164		
Total	15	79.9045			

The analyses also show that 99.96% of the variation of WA may be explained by the factors and interaction appeared in the model (R-sq=99.96%). The adjusted R-sq is calculated as 99.69%, and standard error of estimation is 0.1282. These values validate that the reduced model may be used for prediction of WA response.

In order to optimize WA response itself, a response optimizer is run, and optimal setting for levels of the factors proposed by such module as follows:

Variable	Setting
Cement	1
Aggregate	-1
Water	-1
Admixture	1

Response	Fit	SE Fit	95% CI	95% PI
WA	1.845	0.120	(1.328; 2.361)	(1.089; 2.600)

The results show that, the value of WA response would be 1.845 on average, standard error of estimation 0.12 when Cement and Admixture are set to high levels, Aggregate and Water to low levels. The results also show that, if the setting of the factors are kept as is, the value of WA response would be within 1.328 and 2.361 with 95% CI, 1.089 and 2.600 with 95% PI.

6.3 Analyze Data for Compressive Strength Response

As for FT and WA, the similar methodology is applied for the data of compressive strength (CS) response. The initial ANOVA is given in Table 7.

Table 7 ANOVA for compressive strength response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	5928.99	423.50	74.59	0.091
Linear	4	3393.61	848.40	149.42	0.061
Cement	1	19.99	19.99	3.52	0.312
Aggregate	1	3334.76	3334.76	587.33	0.026
Water	1	38.38	38.38	6.76	0.234
Admixture	1	0.48	0.48	0.08	0.821
2-Way Interactions	6	2467.62	411.27	72.43	0.090
Cement*Aggregate	1	2415.06	2415.06	425.35	0.031
Cement*Water	1	16.95	16.95	2.99	0.334
Cement*Admixture	1	32.32	32.32	5.69	0.253
Aggregate*Water	1	1.96	1.96	0.34	0.662
Aggregate*Admixture	1	0.30	0.30	0.05	0.856
Water*Admixture	1	1.04	1.04	0.18	0.743
3-Way Interactions	4	67.76	16.94	2.98	0.406
Cement*Aggregate*Water	1	2.65	2.65	0.47	0.618
Cement*Aggregate*Admixture	1	14.32	14.32	2.52	0.358
Cement*Water*Admixture	1	7.90	7.90	1.39	0.448
Aggregate*Water*Admixture	1	42.90	42.90	7.55	0.222
Error	1	5.68	5.68		
Total	15	5934.67			

According to Table 7, it can be said that not only some interactions but also main effects (i.e. Cement, Water, and Admixture) are not significant. When the backward elimination approach is run, a proper model may be found for prediction of CS. The reduced model for CS is given in Table 8.

Table 8 ANOVA for reduced model of compressive strength response

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	8	5900.83	737.60	152.60	0.000
Linear	4	3393.61	848.40	175.53	0.000
Cement	1	19.99	19.99	4.14	0.081
Aggregate	1	3334.76	3334.76	689.93	0.000
Water	1	38.38	38.38	7.94	0.026
Admixture	1	0.48	0.48	0.10	0.763
2-Way Interactions	3	2464.33	821.44	169.95	0.000
Cement*Aggregate	1	2415.06	2415.06	499.65	0.000
Cement*Water	1	16.95	16.95	3.51	0.103
Cement*Admixture	1	32.32	32.32	6.69	0.036
3-Way Interactions	1	42.90	42.90	8.87	0.021
Aggregate*Water*Admixture	1	42.90	42.90	8.87	0.021
Error	7	33.83	4.83		
Total	15	5934.67			

According to Table 8, all main effects and most of the interaction effects are significant (p<0.10) where the confidence level is set to 90%. Even though the admixture is insignificant, such factor is included in the model because of the hierarchy property. The regression equation for compressive strength (CS) response including significant factors and interactions is obtained as:

$$\begin{aligned} \text{CS} = {} & 60{,}467 + 1{,}118\ \text{Cement} + 14{,}437\ \text{Aggregate} - 1{,}549\ \text{Water} - 0{,}173\ \text{Admixture} \\ & + 12{,}286\ \text{Cement*Aggregate} + 1{,}029\ \text{Cement*Water} + 1{,}421\ \text{Cement*Admixture} \\ & - 1{,}637\ \text{Aggregate*Water*Admixture} \end{aligned}$$

The analyses show that 99.43% of the variation of CS may be explained by the factors and interaction appeared in the model (R-sq=99.43%). The adjusted R-sq is calculated as

98.78%, and standard error of estimation is 2.1985. It may be said that these values validate the reduced model may be used for prediction of CS response.

In order to optimize CS response itself, a response optimizer is run, and optimal setting for levels of the factors proposed by such module as follows:

Variable	Setting
Cement	1
Aggregate	1
Water	-1
Admixture	1

Response	Fit	SE Fit	95% CI	95% PI
CS	91.71	1.65	(87.81; 95.61)	(85.21; 98.21)

The results show that, the value of CS response would be 91.71 on average, standard error of estimation 1.65 when Cement, Aggregate and Admixture are set to high levels, and Water to low level. The results also show that, if the setting of the factors are kept as is, the value of CS response would be within 87.81 and 95.61 with 95% CI, 85.21 and 98.21 with 95% PI.

6.4 Simultaneous Optimization for all Responses

Although optimization for each response is important, simultaneously optimization is crucial for manufacturing of concrete. Since it is desirable to optimize all responses simultaneously, while flow of concrete and compressive strength are maximized, and water absorption is minimized, the response optimizer module is run one more time by using desirability function approach. As discussed in Chapter 4, the desirability function approach is extensively used in the literature. A detail explanation about desirability function approach may be found in (Myers, et. al, 2009).

As developed by Derringer and Suich (1980), the desirability function, one of the solutions to optimize multiple responses, has been widely used since then in industry (Candioti et. al, 2014).

Desirability optimization methodology is based on the idea that the quality of a product or process that has multiple characteristics, when one of them is outside of some "desired" limits, is completely unacceptable. The method finds operating conditions that provide the "most desirable" response values (Figueiredo et. al, 2014). There are three different types of desirability function available depending on the criteria for responses; larger-the-better (LTB), smaller-the-better (STB), and nominal-the-better (NTB). The NTB is selected to optimize a response considering a target is the criterion, while the LTB is for maximization and STB is for minimization.

Regardless of the criterion, desirability takes values between zero and one. High value of desirability function indicates that the best levels of factors to optimize the system currently studied has been reached. For the task of multi-response optimization using this methodology, firstly, individual desirability function, d_i, is formed according to the optimization criterion for such response. Composite desirability (also called global desirability or overall desirability) is then calculated using the following equation:

$$D = (d_1^{r_1} \text{ x } d_2^{r_2} \text{ x} \ldots. \; d_n^{r_n})^{\frac{1}{\Sigma n}}$$

where r_i is the importance of each response relative to the others. If the importance of the responses is equal to each other, the r values are simply set to 1.

In this subsection, the desirability function approach is applied for the purpose of optimizing all responses with the guidance of Minitab Software. The response optimizer module is run, assuming each response has equal importance relative to the others, while the FT and CS are maximized and the WA is minimized, simultaneously. The optimization plot obtained by means of this module is depicted in Figure 8.

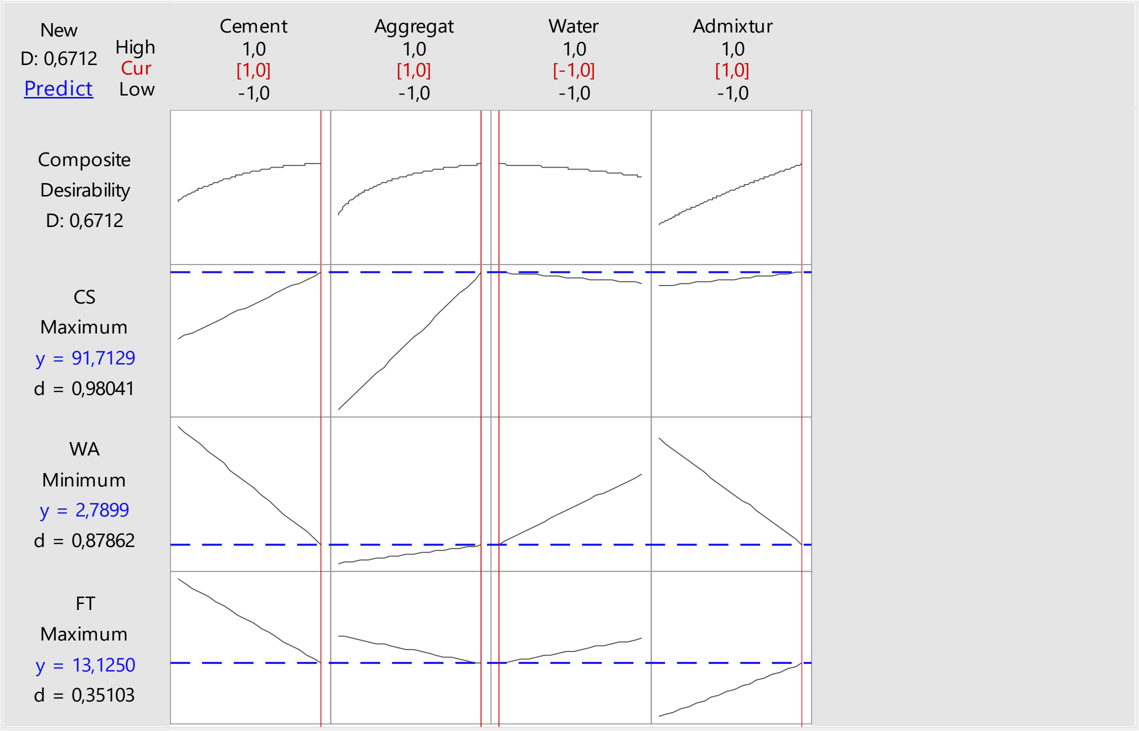

Figure 8 Multi-response optimization plot for three responses

The optimization plot shows the effect of each factor (columns) on the responses or composite desirability (rows). The vertical red lines on the graph represent the current factor settings. The numbers displayed at the top of a column show the current factor level settings (in red). The horizontal blue lines and numbers represent the responses for the current factor level. Individual and composite desirability assess how well a combination of levels of factors fulfills the goals defined for the responses. While individual desirability (d) evaluates how the settings optimize a single response, composite desirability (D) evaluates how the settings optimize all responses simultaneously.

The results for simultaneous optimization obtained from response optimizer and individual optimal settings for three responses are given below for comparison purpose.

Variable	Setting for All Responses	FT	WA	CS
Cement	1	-1	1	1
Aggregate	1	-1	-1	1
Water	-1	1	-1	-1
Admixture	1	1	1	1

It is clearly observed that each response has its own setting when related response is considered. For instance, if the FT were selected as an important response, Cement and Aggregate would have set to low levels, Water and Admixture set to high levels. This setup should be changed when WA is considered as the most important response. On the other hand, the own setting for CS shows a similar structure with simultaneous optimization.

However; since the mortar is prepared based on the same ingredients in terms of Cement, Aggregate, Water, and Admixture, it should be taken into account that the behaviors of responses may be affected by each other. Therefore, it can be said that simultaneous optimization is the only way for finding the optimal setting when there are multi responses.

The optimization plot indicates that the optimal setting for factors (levels in red color) will be high levels for Cement, Aggregate, and Admixture and low level for Water, respectively. The plot also indicates that if this setting is applied, the individual desirability values for FT, WA, and CS are obtained as 0.35103, 0.87862, and 0.98041, respectively. Then, based on the individual desirability values, the composite desirability may be calculated as 0.6712 using such equation. The individual desirability values are acceptable for WA and CS; however, may not be acceptable for FT. On the other hand, since FT may be spread over a large area with the help of worker(s), a target value (i.e. 14 cm) may be set for such response. By this consideration, the response optimizer is rerun and optimization plot obtained is given in Figure 9.

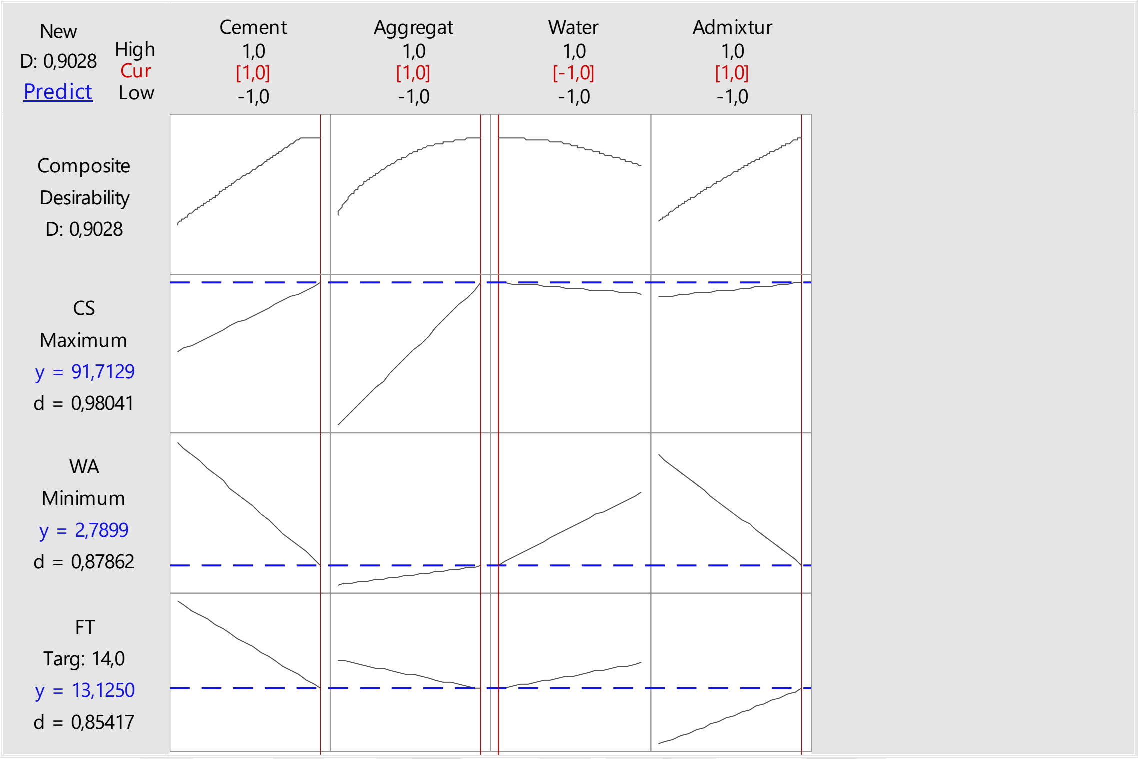

Figure 9 Multi-response optimization plot for three responses (Target=14 cm for FT)

Response	Fit	SE Fit	95% CI	95% PI
CS	91,71	1,65	(87,81; 95,61)	(85,21; 98,21)
WA	2,790	0,120	(2,274; 3,306)	(2,034; 3,545)
FT	13,125	0,816	(10,861; 15,389)	(9,666; 16,584)

It can be said that the optimal setting, in terms of levels of the factors, did not change. However, composite desirability increased about 35%. If the plot is examined closely, it can also be said that the individual desirability values for WA (0.87862) and CS (0.98041) are remained the same, but increased for FT (from 0.35103 to 0.85417). Because of this change, composite desirability also increased from 0.6712 to 0.9028. The higher composite desirability value, the more acceptable setting for all responses is obtained.

6.5 Analyzing Data for Water Absorption Response (28 days)

The experimental data for 28 days are given in Appendix 1. The initial ANOVA table for water absorption is obtained using Minitab Software, and given in Table 9.

Table 9 ANOVA for water absorption response (28 days)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	14	153.265	10.9475	8.11	0.269
Linear	4	36.469	9.1172	6.76	0.280
Cement	1	0.305	0.3053	0.23	0.717
Aggregate	1	34.896	34.8960	25.86	0.124
Water	1	0.730	0.7298	0.54	0.596
Admixture	1	0.538	0.5376	0.40	0.642
2-Way Interactions	6	91.107	15.1844	11.25	0.224
Cement*Aggregate	1	30.871	30.8712	22.88	0.131
Cement*Water	1	2.210	2.2103	1.64	0.422
Cement*Admixture	1	4.346	4.3463	3.22	0.324
Aggregate*Water	1	17.325	17.3248	12.84	0.173
Aggregate*Admixture	1	14.501	14.5012	10.75	0.188
Water*Admixture	1	21.853	21.8527	16.19	0.155
3-Way Interactions	4	25.689	6.4223	4.76	0.330
Cement*Aggregate*Water	1	13.757	13.7566	10.19	0.193
Cement*Aggregate*Admixture	1	7.373	7.3729	5.46	0.257
Cement*Water*Admixture	1	3.332	3.3318	2.47	0.361
Aggregate*Water*Admixture	1	1.228	1.2280	0.91	0.515
Error	1	1.349	1.3495		
Total	15	154.614			

As seen in Table 9, it can be said that neither factors nor interactions effects are significant. In order to find a reduced model, the backward elimination approach is applied. The reduced model is given in Table 10.

Even though almost all main effects, except aggregate, are not significant, they kept in the model because of hierarchy property. On the other hand, four two-level and one three-level interactions included in the model based on 90% CI. The regression equation for water absorption (WA28) response including significant factors and interactions is obtained as:

Table 10 ANOVA for reduced model for water absorption response (28 days)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	134.775	14.9750	4.53	0.040
Linear	4	36.469	9.1172	2.76	0.129
Cement	1	0.305	0.3053	0.09	0.771
Aggregate	1	34.896	34.8960	10.55	0.017
Water	1	0.730	0.7298	0.22	0.655
Admixture	1	0.538	0.5376	0.16	0.701
2-Way Interactions	4	84.550	21.1375	6.39	0.024
Cement*Aggregate	1	30.871	30.8712	9.34	0.022
Aggregate*Water	1	17.325	17.3248	5.24	0.062
Aggregate*Admixture	1	14.501	14.5012	4.39	0.081
Water*Admixture	1	21.853	21.8527	6.61	0.042
3-Way Interactions	1	13.757	13.7566	4.16	0.087
Cement*Aggregate*Water	1	13.757	13.7566	4.16	0.087
Error	6	19.839	3.3065		
Total	15	154.614			

$$\begin{aligned} \text{WA28} = {} & 6.585 - 0.138\ \text{Cement} + 1.477\ \text{Aggregate} + 0.214\ \text{Water} - 0.183\ \text{Admixture} \\ & - 1.389\ \text{Cement*Aggregate} - 1.041\ \text{Aggregate*Water} \\ & - 0.952\ \text{Aggregate*Admixture} \\ & + 1.169\ \text{Water*Admixture} + 0.927\ \text{Cement*Aggregate*Water} \end{aligned}$$

The analyses show that 87.17% of the variation of WA28 may be explained by the factors and interaction appeared in the model. The adjusted R-sq is calculated as 77.92%, and standard error of estimation is 1.82. These values validate that the reduced model may be used for prediction of WA28 response.

In order to optimize WA28 response itself, a response optimizer is run, and optimal setting for levels of the factors proposed by such module as follows:

Variable	Setting
Cement	-1
Aggregate	-1
Water	-1
Admixture	1

Response	Fit	SE Fit	95% CI	95% PI
WA28	1.28	1.44	(-2.24; 4.79)	(-4.40; 6.95)

The results show that, the value of WA28 response would be 1.28 on average, standard error of estimation 1.44 when Cement, Aggregate, and Water are set to low levels, Admixture to high level. The results also show that, if the setting of the factors are kept as is, the value of WA28 response would be as large as 4.79 with 95% CI, 6.95 with 95% PI.

6.6 Analyze Data for Compressive Strength Response (28 days)

As for previous analyses, the similar methodology is applied for the data of compressive strength response (CS28). The results of initial ANOVA is given in Table 11.

Based on the ANOVA given in Table 11, it can be said that almost all main and interactions effects, except Admixture and Cement*Aggregate*Admixture, are significant at 90% CI. When the backward elimination approach is run, a proper model may be found for prediction of compressive strength (CS28). The reduced model is given in Table 12.

Table 11 ANOVA for compressive strength response (28 days)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	13	2479.04	190.70	819.61	0.001
Linear	4	2205.02	551.26	2369.30	0.000
Cement	1	2128.96	2128.96	9150.27	0.000
Aggregate	1	3.81	3.81	16.40	0.056
Water	1	71.46	71.46	307.12	0.003
Admixture	1	0.79	0.79	3.41	0.206
2-Way Interactions	6	260.99	43.50	186.95	0.005
Cement*Aggregate	1	14.89	14.89	64.02	0.015
Cement*Water	1	10.46	10.46	44.96	0.022
Cement*Admixture	1	4.99	4.99	21.46	0.044
Aggregate*Water	1	177.64	177.64	763.49	0.001
Aggregate*Admixture	1	2.90	2.90	12.47	0.072
Water*Admixture	1	50.10	50.10	215.33	0.005
3-Way Interactions	3	13.03	4.34	18.66	0.051
Cement*Aggregate*Water	1	3.12	3.12	13.40	0.067
Cement*Aggregate*Admixture	1	1.37	1.37	5.90	0.136
Cement*Water*Admixture	1	8.54	8.54	36.69	0.026
Error	2	0.47	0.23		
Total	15	2479.50			

Table 12 ANOVA for reduced model of compressive strength response (28 days)

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	2466.65	274.07	127.98	0.000
Linear	4	2205.02	551.26	257.41	0.000
Cement	1	2128.96	2128.96	994.13	0.000
Aggregate	1	3.81	3.81	1.78	0.230
Water	1	71.46	71.46	33.37	0.001
Admixture	1	0.79	0.79	0.37	0.565
2-Way Interactions	4	253.09	63.27	29.55	0.000
Cement*Aggregate	1	14.89	14.89	6.96	0.039
Cement*Water	1	10.46	10.46	4.88	0.069
Aggregate*Water	1	177.64	177.64	82.95	0.000
Water*Admixture	1	50.10	50.10	23.39	0.003
3-Way Interactions	1	8.54	8.54	3.99	0.093
Cement*Water*Admixture	1	8.54	8.54	3.99	0.093
Error	6	12.85	2.14		
Total	15	2479.50			

According to Table 12, factors and interactions effects are significant ($p<0.10$) where the confidence level is set to 90%. Even though Aggregate and Admixture are insignificant, such factors are included in the model because of the hierarchy property. The regression equation for compressive strength (CS28) response including significant factors and interactions is obtained as:

$$
\begin{aligned}
\text{CS28} = {} & 77.238 + 11.535\ \text{Cement} - 0.488\ \text{Aggregate} - 2.113\ \text{Water} - 0.223\ \text{Admixture} \\
& + 0.965\ \text{Cement*Aggregate} + 0.809\ \text{Cement*Water} + 3.332\ \text{Aggregate*Water} \\
& + 1.770\ \text{Water*Admixture} - 0.730\ \text{Cement*Water*Admixture}
\end{aligned}
$$

The analyses show that 99.48% of the variation of CS28 may be explained by the factors and interaction appeared in the model. The adjusted R-sq is calculated as 98.70%, and standard error of estimation is 1.46. It may be said that these values validate the reduced model may be used for prediction of CS28 response.

In order to optimize CS28 response itself, a response optimizer is run, and optimal setting for levels of the factors proposed by such module as follows:

Variable	Setting
Cement	1
Aggregate	-1
Water	-1
Admixture	-1

Response	Fit	SE Fit	95% CI	95% PI
CS28	94.20	1.16	(91.36; 97.03)	(89.63; 98.76)

The results show that, the value of CS28 response would be 94.20 on average, standard error of estimation 1.16 when Cement is set to high level, and Aggregate, Water, and Admixture are to low levels. The results also show that, if the proposed setting is preferred, the value of CS28 response would be within 91.36 and 97.03 with 95% CI, 89.63 and 98.76 with 95% PI.

6.7 Simultaneous Optimization for all Responses (28 days)

In this subsection, the responses for 28 days are simultaneously optimized as explained in subsection 6.4. The response optimizer is applied to minimize WA28 and maximize CS28. Since FT is important for only fresh mixes and previously analyzed, two optimization processes are run in this subsection. Firstly, the FT response is not taken into account for the simultaneous optimization. In the second attempt, the FT response is included in the optimization process as is.

The optimization plot obtained for WA28 and CS28 responses by means of response optimizer is depicted in Figure 10. The results obtained from response optimizer and individual optimal settings for two responses are given below for comparison purpose.

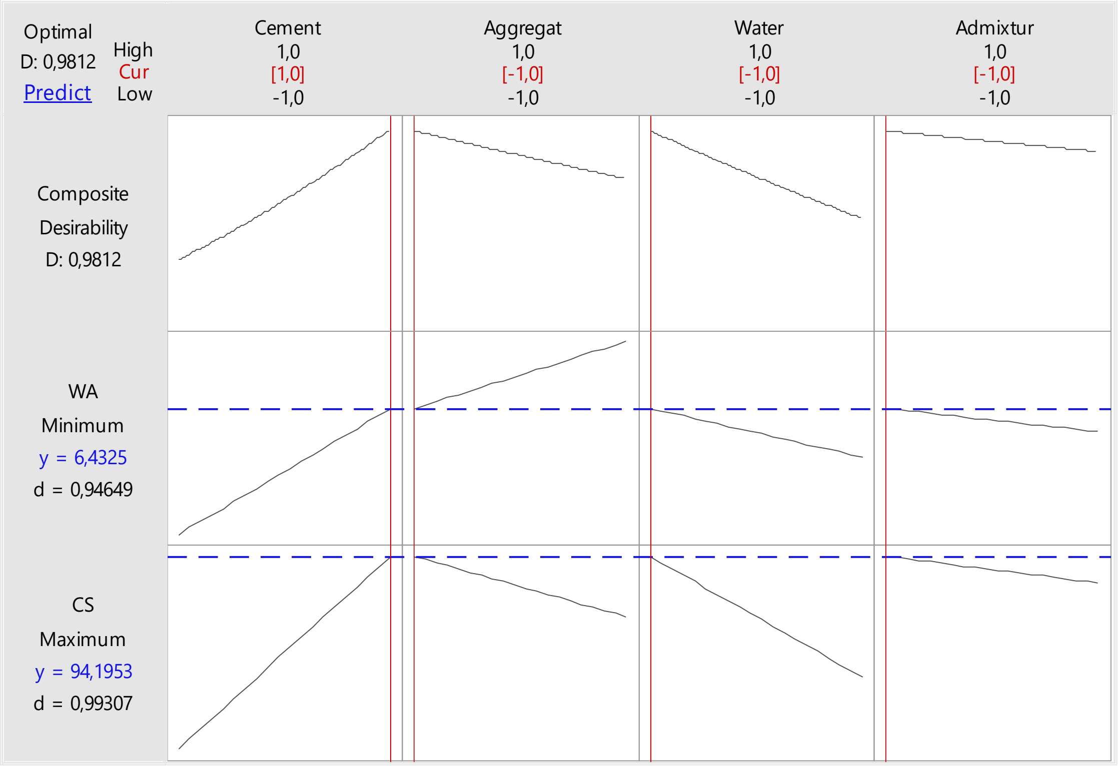

Figure 10 Multi-response optimization plot for WA28 and CS28

Variable	Setting for All Responses	WA28	CS28
Cement	1	-1	1
Aggregate	-1	-1	-1
Water	-1	-1	-1
Admixture	-1	1	-1

Again, it is clearly observed that each response has its own setting when related response is considered. For instance, while the levels of the factors are set to low levels for Cement, Aggregate, and Water, high level for Admixture for WA28, the levels of the factors for CS28 are completely different. On the other hand, the own setting for CS28 also shows a similar structure with simultaneous optimization. As explained before, the simultaneous optimization is considered the only way for finding the optimal setting when there are multi responses.

The optimization plot in Figure 10 shows that the optimal setting for factors (levels in red color) will be at high level for Cement, low levels for Aggregate, Water, and Admixture, respectively. The plot also indicates that the individual desirability values of WA28 and

CS28 are 0.9465, and 0.9931, respectively. Then, based on the individual desirability values, the composite desirability may be calculated as 0.9812 using such equation. The individual desirability values are acceptable for WA28 and CS28.

The optimization plot for WA28, CS28, and FT is given in Figure 11.

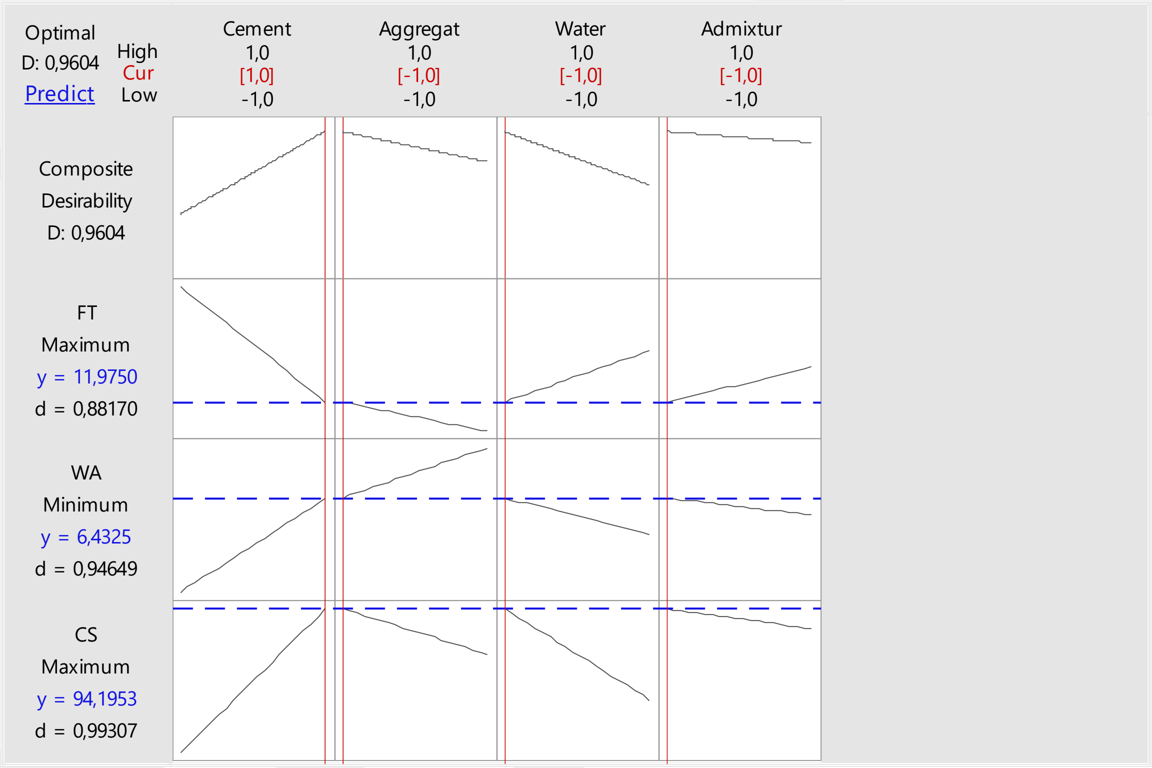

Figure 11 Multi-response optimization plot for WA28, CS28, and FT

Response	Fit	SE Fit	95% CI	95% PI
FT	11.975	0.730	(10.350; 13.600)	(8.863; 15.087)
WA28	6.43	1.44	(2.91; 9.95)	(0.76; 12.10)
CS28	94.20	1.16	(91.36; 97.03)	(89.63; 98.76)

It can be said that the optimal setting, in terms of levels of the factors, did not change. However, the value of composite desirability decreased negligibly, meaning that including the FT into the optimization analysis did not affect much the performances of other responses. If the plot is examined with care, it can also be said that the individual desirability values for WA28 and CS28 are not changed. However, the FT response had an individual desirability of 0.8817, which is better than the result of simultaneous optimization for 7 days analyses.

If Cement is set to high level, and the remaining factors are set to their low levels, the FT would be as large as 13.6 at 95% CI and 15.09 at 95% PI. On the other hand, the WA28 would be 6.43 on average with the error of 1.44, the CS28 be 94.20 on average with the error of 1.16. In addition, the CS28 would be as large as 98.76, while the WA28 would be as small as 0.76 at 95% PI. Since the pieces are left in water for 28 days, the increase for WA28 is expected because pieces waiting in water absorb more water. The increase for CS28 is also expected because pieces waiting in water harden more.

As a conclusion, it can be said that there is a reasonable improvement for concrete pieces for CS, frequently considered the most important response among others for real life applications, the higher strength may be obtained as curing time increases.

CHAPTER 7: Conclusions and Future Work

In the construction sector, responses of flow table, water absorption, and compressive strength are very important. Engineers who make concrete mixes must consider those factors to make strong buildings that are very reliable in construction companies. In construction companies, customer loyalty is very low, because sometimes the buildings collapse due to not building them very well. This study is done to help improving manufacturing process to make reliable concrete for customer satisfaction and profitability of construction companies.

In this study; flow table test, water absorption test, and compressive strength test are carried out for concrete pieces having a curing time of 7 days and 28 days. Minitab software is used to analyze the data obtained from the tests to find the optimal levels of factors for providing better mixes of concrete.

It was seen that the results for 7 days experiment are considered somehow satisfactory. Both data for 7 days and 28 days are analyzed in a similar fashion. First, each response is analyzed separately, then an approach called desirability function is applied for simultaneous optimization of all responses.

The results for individual analyses provided different setting for the factors concerned. For 7 days data, the optimal setting is obtained as high levels for Cement, Aggregate, and Admixture, low level for Water. On the hand, for 28 days data, a different setting is acquired; Aggregate, Water, and Admixture are at low levels, Cement at high level. Based on these settings, it is observed that WA is increased to 6.43 as expected when the curing time is prolonged. On the other hand, CS is also increased to 94.20 as desired. This concludes that when someone wants to make strong mixes, pieces should be kept in water for a long period of time.

As a future study, different ingredients (i.e. Cement, Aggregates, and Admixtures) may be used to obtain better mixtures providing lower WA, and higher FT and CS values. Even though it is time consuming, the effects of longer curing times may also be examined. Addition, different tests (other than FT, WA, and CS) based on the availability of related equipment or machines may be performed to optimize other responses of concrete pieces.

Finally, different types of design of experiments (i.e. response surface methodology, robust design) may be used to look for better combinations of factors for construction companies to be able to get benefit.

Appendix

Design Matrix and 7 Days Data for Three Responses

Cement	Aggregate	Water	Admixture	FT	WA	CS
X	3X	0.5X	0X	18.5	8.49559	65.2083
X	3X	0.5X	0.005X	20	8.673	62.8333
X	3X	0.55X	0X	17.5	8.56732	63.1458
X	3X	0.55X	0.005X	20	8.18367	54.8125
X	2.5X	0.5X	0X	19	8.523	60.9375
X	2.5X	0.5X	0.005X	20	8.70812	58.7292
X	2.5X	0.55X	0X	21.3	8.88338	54.4792
X	2.5X	0.55X	0.005X	22.6	9.97817	54.6458
1.5X	3X	0.5X	0X	8	8.04489	86.25
1.5X	3X	0.5X	0.005X	14	2.83863	92.9167
1.5X	3X	0.55X	0X	14	5.73142	86.25
1.5X	3X	0.55X	0.005X	15	6.28574	87.8125
1.5X	2.5X	0.5X	0X	12	9.98613	37.375
1.5X	2.5X	0.5X	0.005X	14.5	1.79577	31.875
1.5X	2.5X	0.55X	0X	15.5	7.62799	31.4688
1.5X	2.5X	0.55X	0.005X	17	7.3922	38.7292

Design Matrix and 28 Days Data for Two Responses

Cement	Aggregate	Water	Admixture	WA28	CS28
X	3X	0.5X	0X	13,8765	67,0625
X	3X	0.5X	0.005X	8,0673	61,5000
X	3X	0.55X	0X	7,8881	61,5625
X	3X	0.55X	0.005X	8,5255	66,8750
X	2.5X	0.5X	0X	0,9742	76,7500
X	2.5X	0.5X	0.005X	1,6349	69,1875
X	2.5X	0.55X	0X	2,8036	60,5625
X	2.5X	0.55X	0.005X	10,0178	62,1250
1.5X	3X	0.5X	0X	9,0639	87,2500
1.5X	3X	0.5X	0.005X	4,5489	86,3125
1.5X	3X	0.55X	0X	5,9614	90,3125
1.5X	3X	0.55X	0.005X	6,5657	93,1250
1.5X	2.5X	0.5X	0X	6,9804	94,3125
1.5X	2.5X	0.5X	0.005X	5,8280	92,4375
1.5X	2.5X	0.55X	0X	6,6011	81,8750
1.5X	2.5X	0.55X	0.005X	6,0282	84,5625

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