FEBRUARY 2019 M.Sc. in Civil Engineering MUHAMMED BURAK BOZGEYİK

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EXPERIMENTAL EVALUATION AND MODELLING OF THE COMPRESSIVE STRENGTH OF CONCRETES PRODUCED WITH DIFFERENT STRENGTH CLASSES OF CEMENT

M. Sc. THESIS

IN

CIVIL ENGINEERING

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Supervisor
Assoc. Prof. Dr. Kasım MERMERDAŞ

Muhammed Burak BOZGEYiK
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	GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES INSTITUTE **M.Sc. ACCEPTANCE AND APPROVAL FORM**

Civil Engineering M.Sc. (Master of Science) programme student **Muhammed Burak BOZGEYİK** prepared and submitted the thesis titled **"Experimental Evaluation and Modelling of the Compressive Strength of Concretes Produced with Different Strength Classes of Cements"** defended successfully on the date of 07/02/2019 and accepted by the jury as an M.Sc. thesis.

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by this rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Muhammed Burak BOZGEYİK

Signature

ABSTRACT

EXPERIMENTAL EVALUATION AND MODELLING OF THE COMPRESSIVE STRENGTH OF CONCRETES PRODUCED WITH DIFFERENT STRENGTH CLASSES OF CEMENTS

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M.Sc. in Civil Engineering
Supervisor: Assoc. Prof. Dr. Kasım MERMERDAŞ
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The main aim of the thesis is to propose a prediction model for estimation of compressive strength of concretes with various cements and mixture proportions. The strength of the samples produced with three different types of cement at different rates of water-to-cement ratios and cement richness were investigated experimentally and evaluated statistically. Three type of cement possessing 28-day strengths of 32.5, 42.5, and 52.5 MPa was used in the production of concretes. The concretes were produced at cement richness values of 300, 400, and 500 kg/m3 and w/c rates at changing levels within the interval of between 0.3 and 0.6. By this way, combined influences of cement strength, amount of cement and w/c ratio was experimentally investigated. Totally 36 mixes were cast then the compressive strength values were examined after specified moist curing periods (7 and 28 day). A statistical study were conducted on the experimental results and the significances of the cement strength, w/c values and amount of cement on the compressive strength of the concretes were assessed. Another crucial focus of the current paper is to generate an explicit expression to predict the compressive strength of the concretes tackled with the current study. To derive an explicit formula for estimation, a soft computing method called gene expression programming (GEP) was benefited. The GEP model was also compared with a less complicated estimation model developed by multi linear regression method. The results revealed that compressive strength of the samples were significantly influenced by cement type and aggregate-to-cement ratio. The proposed GEP model indicated a high correlation between experimental and predicted values.

Keywords: Compressive Strength, Gene Expression Programming, Multiple Linear Regression, Statistical evaluation

ÖZET

FARKLI DAYANIM SINIFLARI İLE ÜRETİLEN BETONLARIN BASINÇ DAYANIMLARININ DENEYSEL OLARAK DEĞERLENDİRİLMESİ VE MODELLENMESİ

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Tezin temel amacı, çeşitli çimento tipleri ve farklı karışım oranları kullanılarak üretilen betonların basınç dayanımlarını tespit edebilmek için bir tahmin modeli önermektir. Üç farklı tip çimento ile üretilen numunelerin farklı oranlarda su-çimento oranları ve çimento dozajları kullanılarak üretilen betonların dayanımları deneysel olarak incelenmiş ve istatistiksel olarak değerlendirilmiştir. Beton üretiminde 28 günlük dayanımları 32,5, 42,5 ve 52,5 MPa olan üç tip çimento kullanılmıştır. Betonlar, 300, 400 ve 500 kg/m^3 çimento dozajlarında ve 0,3 ile 0,6 arasında değişen seviyelerde su/çimento oranlarında üretilmiştir. Bu şekilde, çimento mukavemeti, çimento miktarı ve s/ç oranının birleşik etkileri deneysel olarak incelenmiştir. Toplam 36 karışım hazırlanmış belirlenen ıslak kürlemeden sonra (7 ve 28 gün) basınç dayanımı değerleri tespit edilmiştir. Deneysel sonuçlar üzerinde istatistiksel bir çalışma yapılmış ve betonların basınç dayanımı üzerinde çimento mukavemeti, s/ç değerleri ve çimento miktarının etkileri değerlendirilmiştir. Mevcut çalışmada ele alınan betonların basınç dayanımını tahmin etmek için matematiksel bir ifade elde edilmiştir. Tahmin için açık bir formül elde etmek için, gen ekspresyonu programlama (GEP) adı verilen esnek bir hesaplama yönteminden yararlanılmıştır. GEP modeli ayrıca, çoklu doğrusal regresyon yöntemiyle geliştirilen daha az karmaşık bir tahmin modeliyle de karşılaştırılmıştır. Sonuçlar, numunelerin basınç dayanımının çimento tipi ve toplam-çimento oranından önemli ölçüde etkilendiğini ortaya koymuştur. Önerilen GEP modeli ile elde edilen deneysel değerler arasında yüksek bir korelasyon olduğu görülmüştür.

Anahtar Kelimeler: Basınç Dayanımı, Gen Ekspresyon Programlama, Çoklu Doğrusal Regresyon, İstatistiksel Değerlendirme

To My Family

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First and foremost, I would like to express my deepest gratitude to my advisor, Assoc. Prof. Dr. Kasım MERMERDAŞ for his helpful comments, criticisms, generous guidance and many creative insights offered during this thesis, guidance and encouragement in carrying out this project.

I sincerely thanks my family to be as a support on me and effort time with me.

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LIST OF SYMBOLS/ABBREVIATIONS

ACI	American Concrete Institute
ANN	Artificial Neural Networks
C_3A	Tricalcium Aluminate
CaO	Calcium Oxide
$CaSO_4$	Calcium Sulfate
CEM	Calcium enriched mixture
CKs	Calcined kaolins
Dmax	Greatest aggregate particle size
f_{ck}	Characteristic pressure resistances
f_{cm}	Target pressure resistances
GEP	Gene expression programming
HPC	High Performance Concrete
MK	Metakaolin
MT	Model Tree
NLR	Non-linear Regression
PC	Portland cement
RAC	Recycled aggregate concrete
SCC	Self Compacting Concrete
SF	Silica fume
SiO_2	Silicium Dioxide
SP	Superplasticizer
w/b	Water-to binder ratio
w/c	Water-to cement ratio
VRMs	Vertical roller mills

CHAPTER 1

INTRODUCTION

1.1 General

The compressive strength of the cement is directly influencing the concrete and mortar characteristics especially the compressive strength characteristic (BS EN 197–1, 2000; Hirschi et al., 2005). During the recent years, different cement strength classes of 32.5, 42.5, and 52.5 MPa have been used in various construction types. In addition to cement strength class, the water-to-cement ratio and cement content are other important factors those affect the concrete properties. There are many studies evaluating the effects of water-to-cement ratio and cement content on the compressive strength. However, the combined effect of water-to-cement ratio, cement content and compressive strength of cement on compressive strength of concrete is still insufficient. Mermerdaş et al. (2012) modeled compressive strength of metakaoline and calcined kaolins modified concrete by means of Gene Expression Programming (GEP). They indicated that GEP is an effective tool for prediction of the compressive strength of concrete. Sayed (2003) investigated the predictability of compressive strength of concrete containing different matrix mixtures by using statistical modeling methods. Eight different parameters of time, water, cement, metakaolin, silica fume, superplasticizer, and fine and coarse aggregates were used in this study. According to findings in this research, statistical modeling is capable for prediction the compressive strength of concrete. Deshpande et al. (2014) used 3 different data driven techniques such as Artificial Neural Networks (ANN), Model Tree (MT), and Non-linear Regression (NLR) for prediction of the 28-day compressive strength of recycled aggregate concrete. Their study indicated that with minimum amount of input parameters (9 mandatory parameters), ANN predicts compressive strength of recycled aggregate concrete better than MT and NLR. However, MT and NLR techniques have advantageous aspects such as MT technique could build a family of models of varying complexity and accuracy, and NLR technique could build a single equation which can be readily used. Chandwani et al. (2014) conducted a study to model compressive strength of self-compacting concrete (SCC), high performance concrete (HPC), and recycled aggregate concrete by using ANN. They used non-destructive test data in the evaluation of the model. According to this study, the ANN is an effective technique that can be used as a predicting tool based on historical data, to estimate the compressive strength of different types of concretes based on mix proportions.

In this study, the effect of water-to-cement ratio, cement content, and cement type on compressive strength of concrete was experimentally investigated. For this reason, three main concrete mixture groups were determined with respect to cement type of CEM II 32.5, CEM I 42.5 and CEM I 52.5. The cement types were selected regarding to 28-day compressive strength. In each concrete mixture group, four different water-to-cement ratios of 0.3, 0.4, 0.5, and 0.6 and three different cement contents of 300, 400, and 500 kg/m3 were considered as experimental parameters. Totally 36 different concrete mixtures were designed and their compressive strengths were measured at the age of 7 and 28 days. After the experimental investigation of the mixtures, the results were used in the modeling of the compressive strength of concrete regarding to input parameters of the cement compressive strength, water-to-cement ratio, aggregate-to-cement ratio, and age by using GEP and regression analysis (RA). The results indicated that compressive strength of the concrete is directly influenced by water-to-cement ratio, age, and especially the cement compressive strength. Two different models were obtained from GEP and RA and their results were compared by graphically and statistically.

1.2 Outline of the Thesis

Introduction chapter is followed by literature review. Then we explained our experimental study and illustrated its results on the following chapter. Chapter 5 represents the Statistical evaluation and multiple linear regression (MLR), while succeeding chapter is related to the derivation of prediction model. Finally, analysis regarding to the correlation between predicted and experimental compressive strength is followed by conclusion.

CHAPTER 2

LITERATURE REVIEW

2.1 Production Process

Cement sets after a couple of hours when mixed with water. Then it hardens in a few days and turns out to be a solid, strong material. As a hydraulic binder (sets when reacts with water), cement binds fine sand and coarse aggregates together in concrete. Cement production steps (Figure 2.1) are as follows:

- Quarrying of limestone and shale
- Engraving for clay and marl
- Grinding
- Blending of components
- Fine milling
- Burning
- Finish milling
- Packing and/or transporting

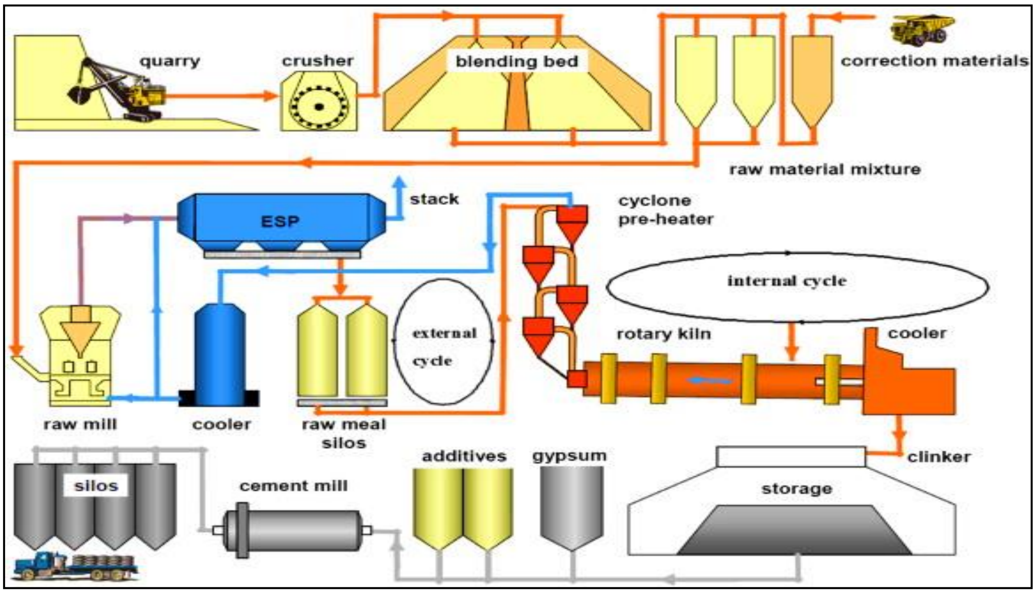


Figure 2. 1. Schematically vision of cement production processes (http://yuvaratna.birlawhite.com/project/white-cement-a-force-multipler-to-sustainable- development-151)

2.1.1 Quarrying of Raw Materials

In quarrying of limestone and shale stage, blasting agents are used to blast the rocks from the ground. Then, the dump trucks or small railroad cars are loaded by using huge power shovels, and the cement is transported to a nearby plant. In order to dug clay and marl, out of the ground, power shovels are used. Final stage is the transportation of raw materials to the plant.

2.1.2 Grinding

Different types of raw material grinding systems are used for crushing. However, the most widely used grinding systems for the finish milling of cement is vertical roller mills (VRMs) (Schneider, 2015). After transporting the raw materials to the plant, the limestone and shale needs to be crushed into smaller parts. Very large pieces are separated and dumped into primary crushers again to decrease in size. Finally, pieces are carried to secondary crushers to make them even more smaller.

2.1.3 Blending

After crushing, the rocks and raw materials are analyzed by plant chemists to see mineral content and raw material proportions. Finally, several raw materials are then mixed to gain a uniform cement. Now the mixture is ready for fine etching.

2.1.4 Fine Milling

After blending the raw materials, they must be grounded into a fine powder by using wet or dry process methods. The wet process is preferred in case clay and marl exist in the composition. Blended raw materials are then poured into mills (cylindrical rotating drums that include steel balls) in wet process. Steel balls that exist in the drum grind the raw materials into smaller fragments. After the grinding, water is added to obtain a slurry form. Resulting slurry is maintained in open tanks. This is required to allow the mixture for additional mixing.

Finally, before burning, some of the water may be removed from the slurry or the kiln may be used to allow water evaporate during burning.

The dry process, on the other hand, is also conducted by using a similar set of mills. However, milling process doesn't require water. The dry materials are stored in silos in order to allow additional mixing and blending in case it is needed.

2.1.5 Burning

The most important issue in cement making process is the burning of blended materials. Regardless of wet or dry, the mix is sent to the rotary kiln. Rotary kiln is one of the biggest pieces of moving machinery that is in use in the sector. The schematic vision of a rotary kiln is shown in the Figure 2.2. It is generally 3-7 meter in diameter and 50-75 meter in length. It is made of steel and lined with firebrick.

The materials roll and slide downward as the kiln revolves. It usually takes four hours. The materials become incandescent. And their color change from purple to violet and finally to orange during the burning process. During the process the heat can reach 1550˚C. The gases that change the properties of the raw materials are driven from the raw materials during this process. The resulting products turn the kiln out to a rounded material. This material is called clinker (Kääntee et al., 2004). The clinker is a marble-sized, glass-hard balls that are tougher than the quarried rock. Then the clinker goes into the cooler to make it ready for storage. In the next stage clinker is milled with gypsum and other mineral additives for getting cement (Alsop, 1998).

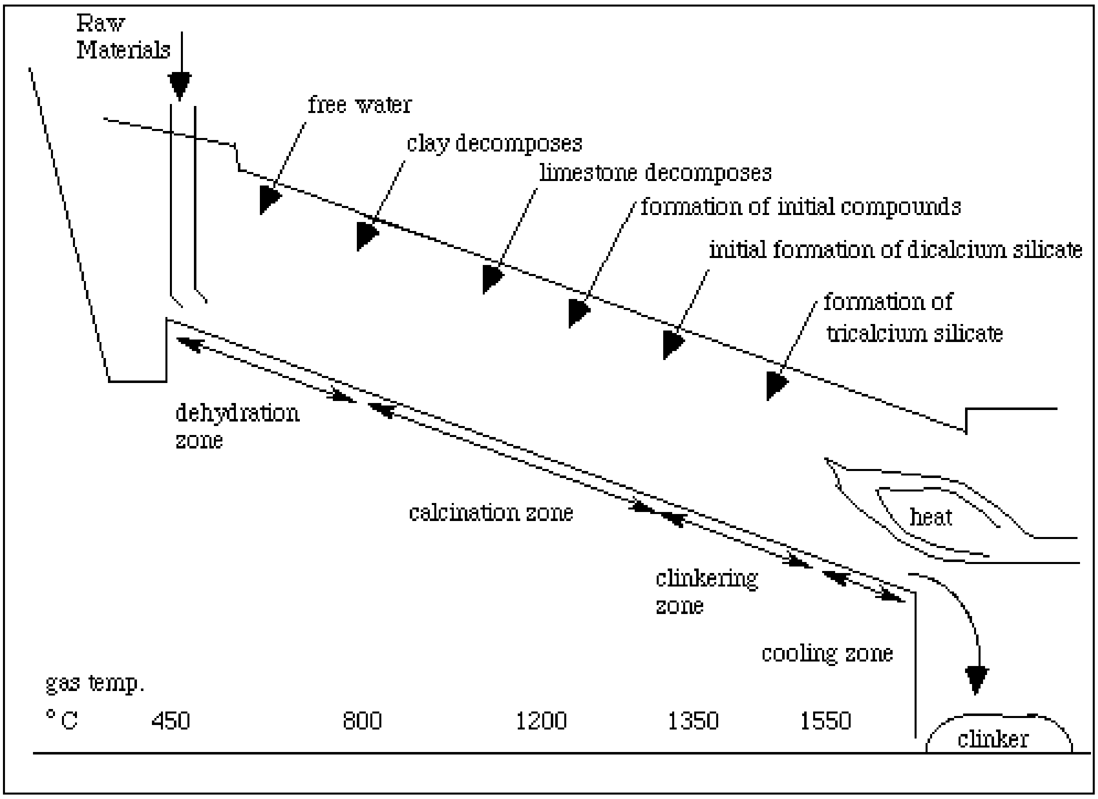


Figure 2. 2. Schematic representation of a rotary kiln
(http://matse1.matse.illinois.edu/concrete/5.gif)

2.1.6 Finish Milling

A little amount of gypsum is then added into the mixture. This process is required to regulate the setting time when the cement gets in contact with water for concrete casting. This process also involves primary as well as secondary grinders. After going through the primary grinders, the clinker turns out to the fineness of sand while after secondary grinders it turns out to fineness of powder.

2.1.7 Packing and Transporting

When the final product is ready to go to market, it is transported either in bulk or in strong paper bags. In case bulk is used, ships, barges, trucks and train can be used.

2.2 Cement Types in Turkish Standards 197 (TS EN 197)

There exist significant standards to generate cement. The cement standards are prepared by technical committee TC 51 of the European Committee for Standardization. These standards are adopted by European countries after 1973. However, there exist many cement types already in use in European Countries that are prepared to conform local standards. Hence, the committee defined a high number of cement types in EN 197-1. These general-purpose standards are accepted directly by Turkey, because it superseded general-purpose Turkish cements.

This new general-purpose cement, in TS EN 197-1, is called “Calcium Enriched Mixture (CEM) Cement”. CEM Cement means the cement the hydraulic hardening of which occurs primarily because of the hydration of calcium silicates and which is required to contain minimum 50% reactive calcium oxide (CaO) and reactive silicone dioxide (SiO_2) by mass. The mixture includes Portland cement (PC) clinker, calcium sulphate ($CaSO_4.2H_2O$) and several mineral additives. In keeping with the standard, CEM Cements have 5 main and 27 sub-types (Table 2.1).

Table 2. 1 Overall cement types according Turkish Standards (TS EN 197-1, 2002)

Main Types	Name of 27 Sub-Types and Theirs Symbols		Composition Ratio by Mass(%)										
			Main Components										Minor Additional Components
			Clinker	Granulated Blast Furnace Slag	Silica Fume	Pozzolana: Natural	Pozzolana: Naturally Calcined	Fly Ash: Siliceous	Fly Ash: Calcareous	Baked Shale	Limestone		
			K	S	D	P	Q	V	W	T	L	LL	
CEM I	Portland Cement	CEM I	95-100	-	-	-	-	-	-	-	-	-	0-5
CEM II	Portland Slag Cement	CEM II/A-S	80-94	6-20	-	-	-	-	-	-	-	-	0-5
		CEM II/B-S	65-79	21-35	-	-	-	-	-	-	-	-	0-5
	Portland Silica Fume Cement	CEM II/A-D	90-94	-	6-10	-	-	-	-	-	-	-	0-5
	Portland Pozzolanic Cement	CEM II/A-P	80-94	-	-	6-20	-	-	-	-	-	-	0-5
		CEM II/B-P	65-79	-	-	21-35	-	-	-	-	-	-	0-5
		CEM II/A-Q	80-94	-	-	-	6-20	-	-	-	-	-	0-5
		CEM II/B-Q	65-79	-	-	-	21-35	-	-	-	-	-	0-5
	Portland Fly Ash Cement	CEM II/A-V	80-94	-	-	-	-	6-20	-	-	-	-	0-5
		CEM II/B-V	65-79	-	-	-	-	21-35	-	-	-	-	0-5
		CEM II/A-W	80-94	-	-	-	-	-	6-20	-	-	-	0-5
		CEM II/B-W	65-79	-	-	-	-	-	21-35	-	-	-	0-5
	Portland Baked Shale Cement	CEM II/A-T	80-94	-	-	-	-	-	-	6-20	-	-	0-5
		CEM II/B-T	65-79	-	-	-	-	-	-	21-35	-	-	0-5
	Portland Calcareous Cement	CEM II/A-L	80-94	-	-	-	-	-	-	-	6-20	-	0-5
		CEM II/B-L	65-79	-	-	-	-	-	-	-	21-35	-	0-5
		CEM II/A-LL	80-94	-	-	-	-	-	-	-	-	6-20	0-5
		CEM II/B-LL	65-79	-	-	-	-	-	-	-	-	21-35	0-5
	Portland Composite Cement	CEM IVA-M	80-88	12-20									0-5
		CEM IVB-M	65-79	21-35									0-5
CEM III	Granulated Blast Furnace Slag Cement	CEM III/A	35-64	36-65	-	-	-	-	-	-	-	-	0-5
		CEM III/B	20-34	66-80	-	-	-	-	-	-	-	-	0-5
		CEM III/C	5-19	81-95	-	-	-	-	-	-	-	-	0-5
CEM IV	Pozzolanic Cement	CEM IV/A	65-89	-	11-35					-	-	-	0-5
		CEM IV/B	45-64		36-55					-	-	-	0-5
CEM V	Composite Cement	CEM V/A	40-64	18-30	-	18-30			-	-	-	-	0-5
		CEM V/B	20-38	31-49	-	31-49			-	-	-	-	0-5

Here: A: Cement type that contains minimum mineral additives

B: Cement type that contains mineral additives more than cement type A.

C: Cement type that contains mineral additives more than cement type B.

TOC: Total Organic Carbon.

CEM I: This group contains a maximum of 0-5% mineral additives. Due to etching clinker solely with $CaSO_4$, PC is obtained.

CEM II: Additives in this group range between 6-35%. Due to additive type, CEM II cements are labeled as Portland Slag or Portland Pozzolanic, cement.

CEM III: The amount of minerals are 36% to 95%. Blast furnace slag cements are belongs to this group.

CEM IV: Cements in this group doesn't include slag or limestone as an additive. The amount of additives differs between 11-55% including pozzolana and fly ash. Hence, Pozzolanic cements are in this group.

CEM V: Composite cements are a member of this group. According to specified limits, slag (18-50%), pozzolana and fly ash (18- 50%) are added to this group of cements. The quantities of additives are adjusted to keep the rate between 20- 64%.

In addition, there exist 5 other types of cement that are generated for specific use. The mineral additives could be added while producing clinker or afterwards. It is included in TS EN 197-1. These types are given below:

- Sulphate-resistant Cements: These types are acquired as clinker produced with limited quantity of Tricalcium aluminate (C_3A) (max 5%) is ground with $CaSO_4.2H_2O$.

- White PC: This type is acquired as white-like clinker produced by firing special quality clay and limestone together is ground with a pre-defined amount of $CaSO_4.\ 2H_2O$.

- Mortar Cement: This type is a finely-ground hydraulic binder involving PC clinker required to improve strength. By mixing only sand and water, this type enables to make ready mortar in order to use in several coating works.

- Blast furnace slag blended cement: The basic features of this type of cements is; limited hydration temperature, blast furnace slag addition and low early strength.

- Low heat of hydration cements: Due to the hydration reactions that occur when mixed with water, these types of cements retain and enhance their strength and stability even under water after hardening.

2.3 Concrete Mix Design Procedures

The calculation of mixture is done for determining the quantity of aggregate, water, air and additives. And if necessary the calculation allows us to obtain the cheapest concrete with a better viscosity, serviceability, resistance, durability, volume stability and the other necessary features (TS 802, 2009). For instance, a concrete mix of proportions 2:3:5 means that cement, fine and coarse aggregate rates are 2, 3 and 5 respectively. The rate of water-cement ratio is often expressed in mass. Finally, the proportions of the mix are determined either by volume or by mass.

2.3.1 Concrete Mix Design According to Turkish Standard 802 (TS 802)

Turkish Standard 802 (TS 802) defines principles of proportioning of concrete mix design. In case the mix performed considering TS 802 sizes and dimensions of structural elements, environmental, physical and chemical effects are considered as main criteria. The concrete design according to TS 802 includes eight steps that are summarized as shown in Figure 2.3.

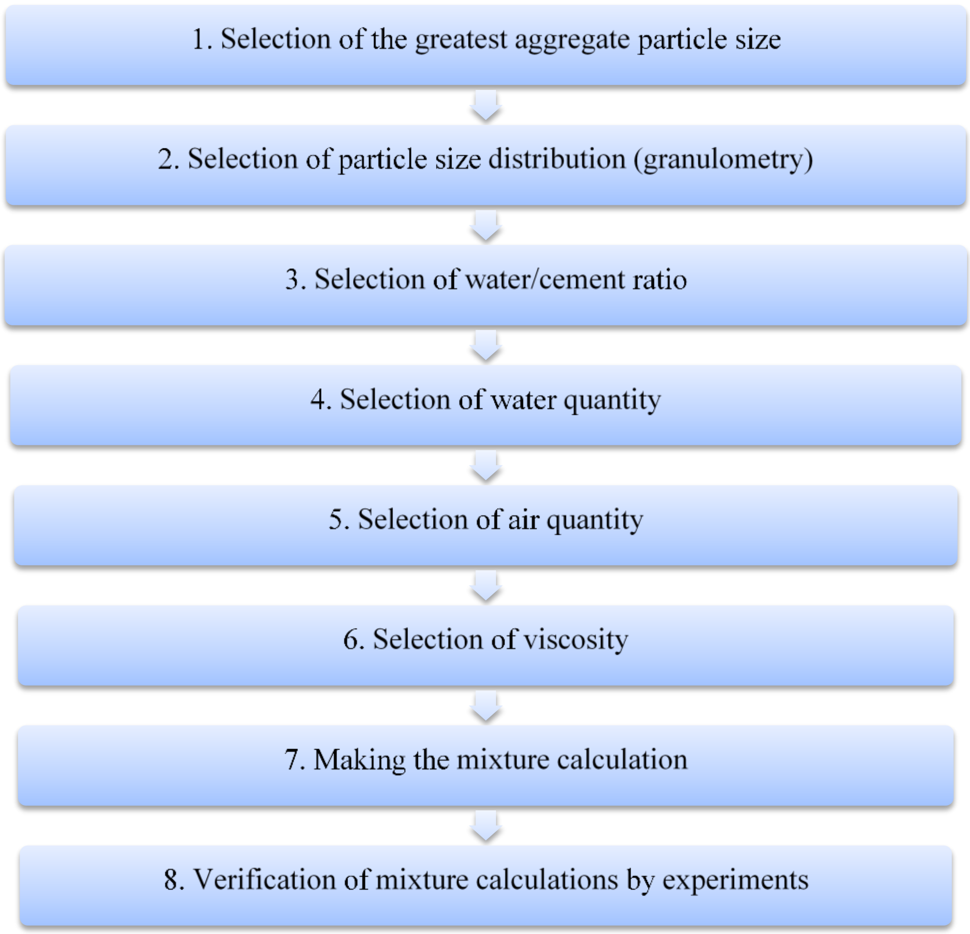


Figure 2. 3. Concrete mixture design flow chart (TS 802)

2.3.1.1 Determining the Greatest Aggregate Particle Size (D_{max}):

First step of the mix design according TS 802 is deciding maximum aggregate particle size. D_{max} is the smallest sieve size that allow whole aggregate to pass through. Parameters such as the type and dimensions of structural elements effect the selection of the D_{max}. D_{max} must be smaller than 1/5 of the wideness, 1/3 of the slab thickness and 3/4 of the minimum spacing of reinforcement. According to TS 802, the table of the maximum aggregate particle size for various structural elements is given in Table 2.2.

Table 2. 2 Diversified structural components dimensions and D_{max} size (TS 802, 2009)

The narrowest size of structural element (mm)	D_{max} (mm)			
	Shear walls, joists and columns	Heawily reinforced slab	Loosely reinforced and non-reinforced slab	Non-reinforced concrete walls
60-140	16	16	32	16
150-290	32	32	63	32
300-740	63	63	63	63

2.3.1.2 Determining Particle Distribution:

The grading of the aggregate has a direct effect on serviceability and durability of the final product. The sorting of the aggregate might be determined according to the limits given in Figures 2.4, 2.5, 2.6, 2.7. The aggregate grading of the mixture preferably should be around zone number 3 given in the figures. Because it will not only contribute to the serviceability but also to the strength of concrete. However, in case it is not possible, one shouldn't exceed the zone number 4.

In Figures 2.4 and 2.7, zone numbers 1, 2, 3, 4, 5 illustrate too coarse grading, graded, appropriate, suitable usable and a very fine grading respectively.

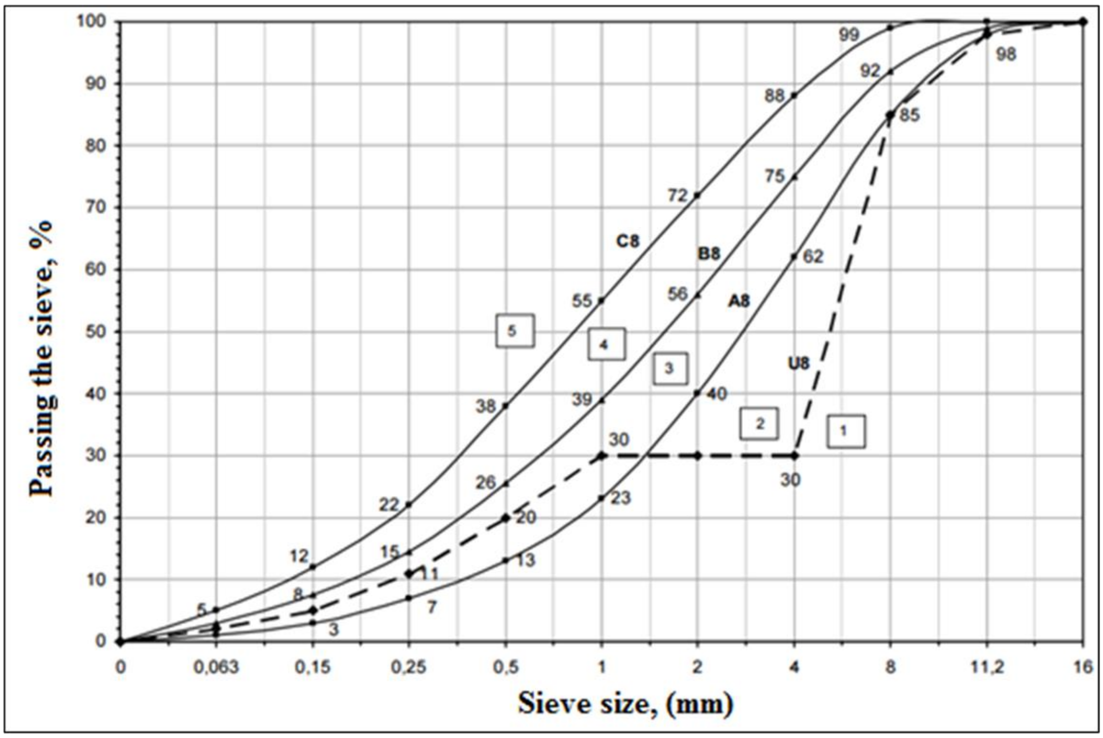


Figure 2. 4. Concrete with the Dmax of 8 mm aggregate reference curves (TS 802, 2009)

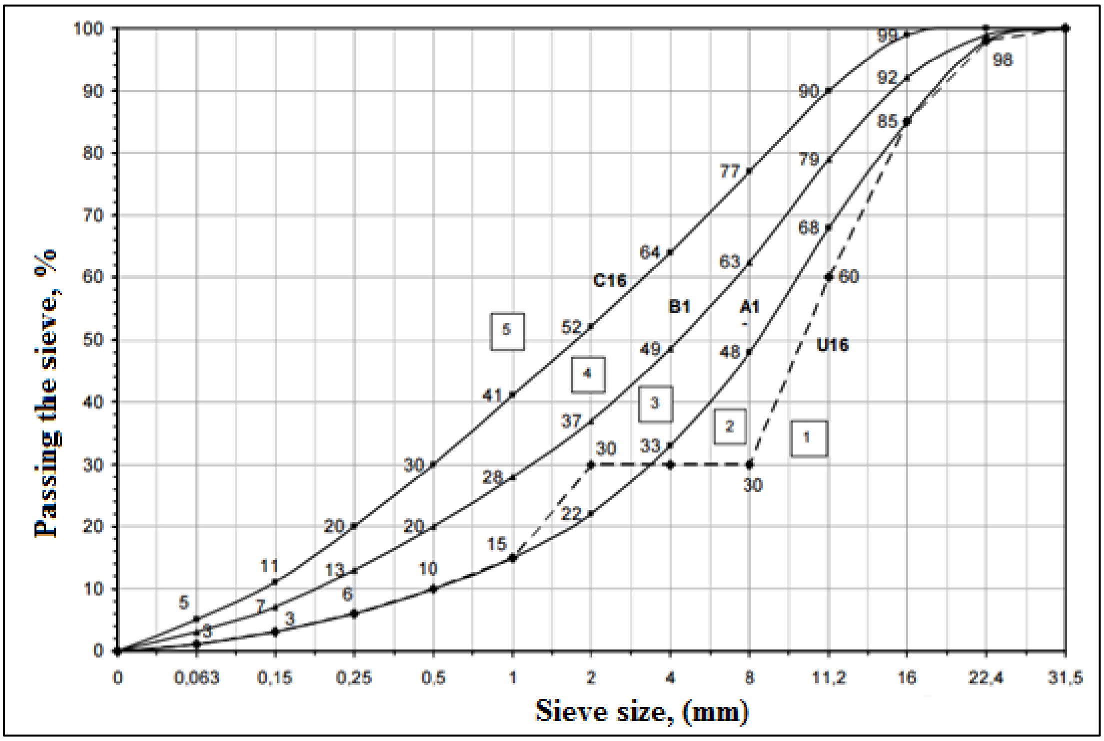


Figure 2. 5. Concrete with the Dmax of 16 mm aggregate reference curves (TS 802, 2009)

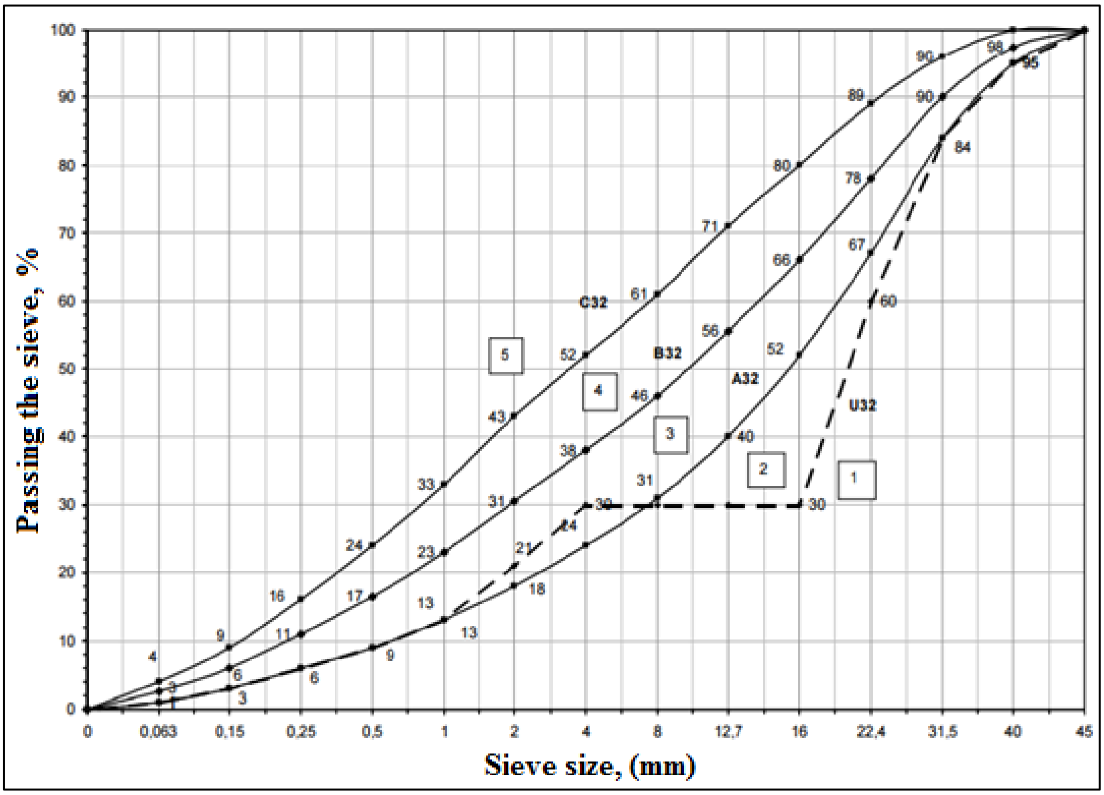


Figure 2. 6. Concrete with the Dmax of 32 mm aggregate reference curves (TS 802, 2009)

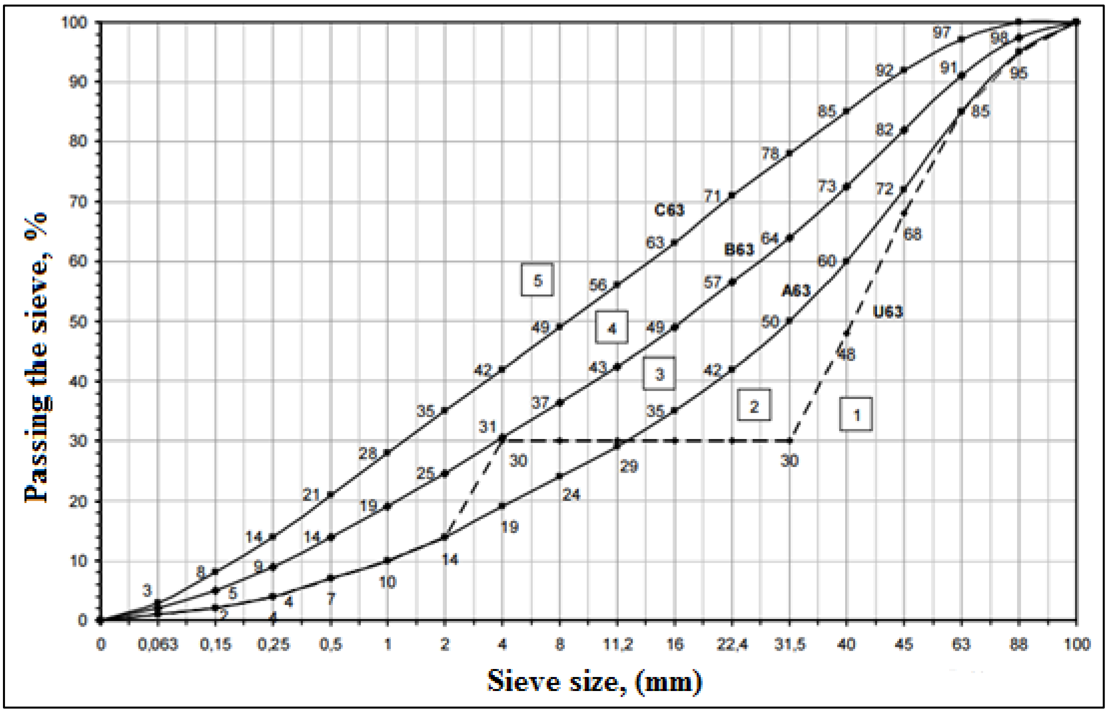


Figure 2. 7. Concrete with the Dmax of 64 mm aggregate reference curves (TS 802, 2009)

Sometimes, concrete need to be poured by pump. There exist limits according to the classification for these cases. The limits for fine and coarse aggregate classes are given in Table 2.3. Curves also are illustrated in Figure 2.8 and 2.9

Table 2. 3 Classification limits of aggregate mixtures recommended for shotcrete (TS 802, 2009)

Sieve Size (mm)	**Passing Percentage , %(cumulative)**	
	Maximum Size 31,5 mm	Maximum Size 22,4 mm
45	100	---
31,5	90 - 97	100
22,4	80 - 90	89 – 96
16	68 - 82	73 – 86
8	52 - 69	54 – 71
4	37 - 56	37 – 56
2	26 - 43	25 – 43
1	17 - 33	16 – 32
0,5	10 - 23	10 – 22
0,25	6 - 16	6 – 15
0,15	3 - 10	3 – 10
0,063	1 - 5	1 – 5
Pan	0	0

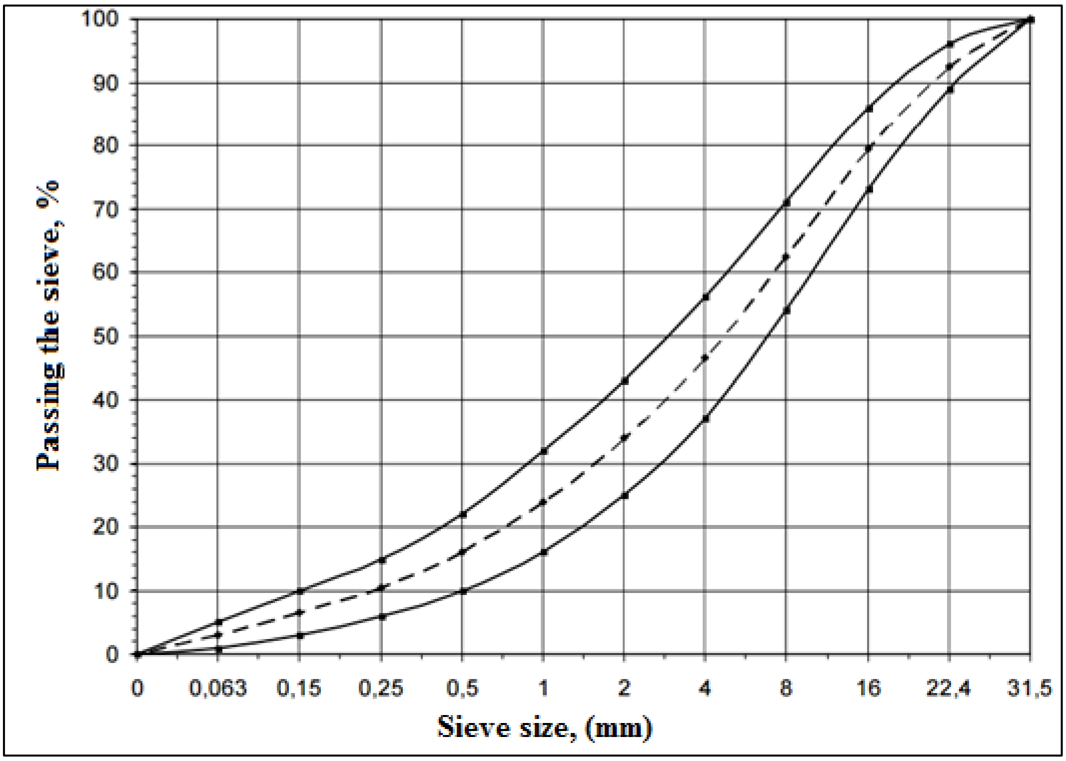


Figure 2. 8. Dmax of 22,4 mm recommended aggregate mixture reference curve in concrete for shotcrete (TS 802, 2009)

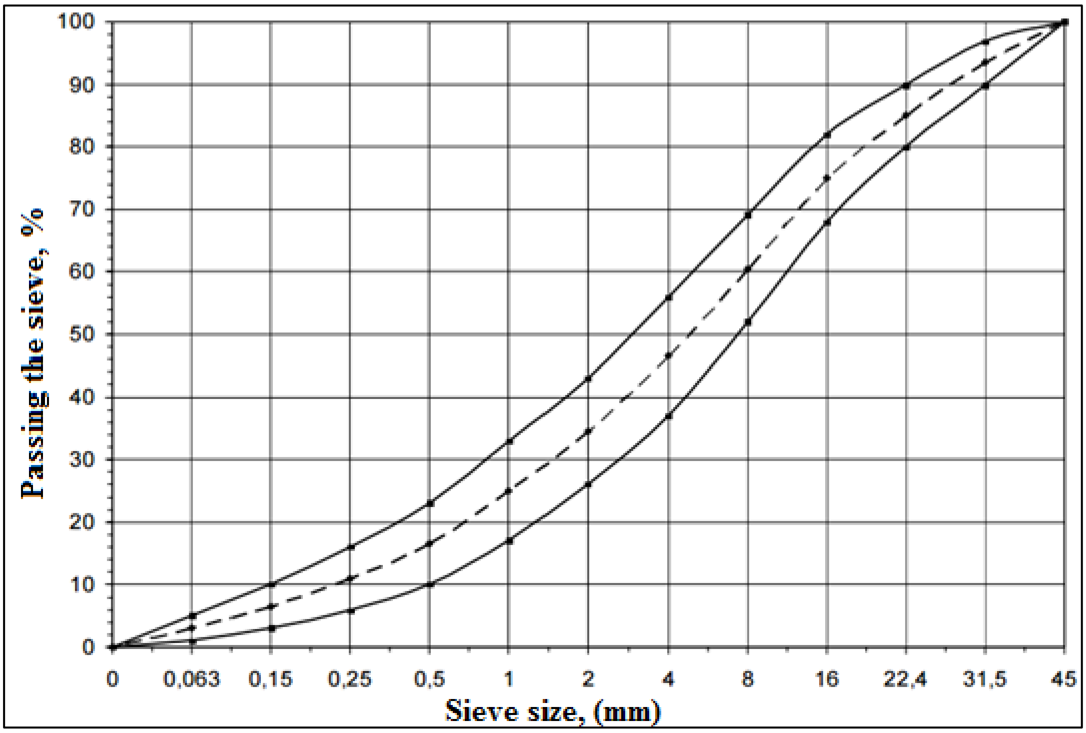


Figure 2. 9. Dmax of 31,5 mm recommended aggregate mixture reference curve in concrete for shotcrete (TS 802, 2009)

2.3.1.3 Determination of Water/Cement (w/c) Ratio:

This ratio is not only related to the class of the concrete but also the intensity of environmental and chemical impacts. Hence, while determining water/cement ratio and other features of the final product climate and environmental conditions also need to be considered. The characteristic compressive strength (f_{ck}) as well as target compressive strength (f_{cm}) are illustrated in Table 2.4 according to the class.

Table 2.5 illustrate the highest water/cement ratio which can be determined considering the concrete compressive strength for 28 days not only for air-entrained but also for other type of concrete. Among the most important factors that affect the strength and durability of the concrete is water/cement ratio (Erdoğan, 2004). Generally, the increase in water/cement ratio makes an adverse effect on strength and durability of the final product. However, the serviceability of concrete decreases and undesired pares possibly occur in case of very low water/cement ratio usage, in case of insufficient compaction.

Table 2. 4 The target and the average compressive strengths required for samples (TS 802, 2009)

Concrete Class	Characteristic Compressive Strength, f_{ck} (MPa)		Target Compressive Strength, f_{cm} (MPa)		
	Characteristic Cylinder (ϕ150x300 mm) Pressure Resistance, f_{ck}(MPa)	Equivalent Cube (150*150*150 mm) Pressure Resistance f_{ck} (MPa)	For Known Standard Deviation	For Unknown Standard Deviation	
				Cylinder (ϕ150x300 mm)	Equivalent cube (150*150*150 mm)
C 14/16	14	16	$f_{cm} = f_{ck} + 1{,}48\sigma$	18	20
C 16/20	16	20		20	24
C 18/22	18	22		22	26
C 20/25	20	25		26	31
C 25/30	25	30		31	36
C 30/37	30	37		36	43
C 35/45	35	45		43	53
C 40/50	40	50		48	58
C 45/55	45	55		53	63
C 50/60	50	60		58	68
C 55/67	55	67		63	75
C 60/75	60	75		67	83
C 70/85	70	85		78	93
C 80/95	80	95		88	103
C 90/105	90	105		98	113
C 100/115	100	115		108	123

Table 2.5 28 days concrete's approximate water to cement ratio according to the compressive strength (TS 802, 2009)

Pressure resistance (28 days) (ϕ150x300 mm) Cylinder (MPa)	Water/cement proportion	
	Non-air-entrained concrete	Air-entrained concrete
45	0.37	---
40	0.42	---
35	0.47	0.39
30	0.54	0.45
25	0.61	0.52
20	0.69	0.60
15	0.79	0.70

2.3.1.4 Determining Water Quantity

The amount of water in a concrete is determined according to the viscosity class, the classification and also the shape and type of the aggregate, the ratio of fine / rough aggregate and finally the amount of air added. In addition, the amount of water has a direct effect on the serviceability, resistance and durability of the final product. Figure 2.10, 2.10, 2.11, and 2.13 illustrate different values of slump that are required in 1 m^3 of concrete mixture composed of natural and angular aggregate.

Besides, Figures below illustrate values in which the water amounts for the greatest aggregate particle size. It is very important to consider that the amount of water in these graphs are calculated for mixtures that doesn't include chemical additives. If chemical additives exist in the mixture, less amount of water may be used according to the graphs. Finally, additive type and dosage also should be considered.

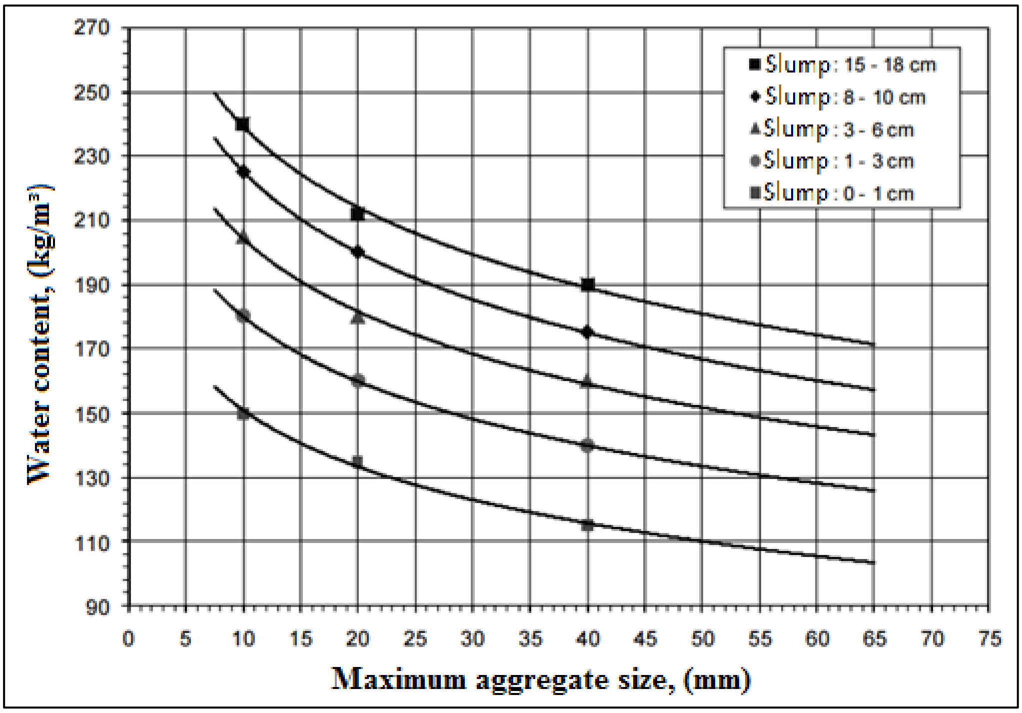


Figure 2.10. Mixing water for non-air-entrained concrete (TS 802, 2009)

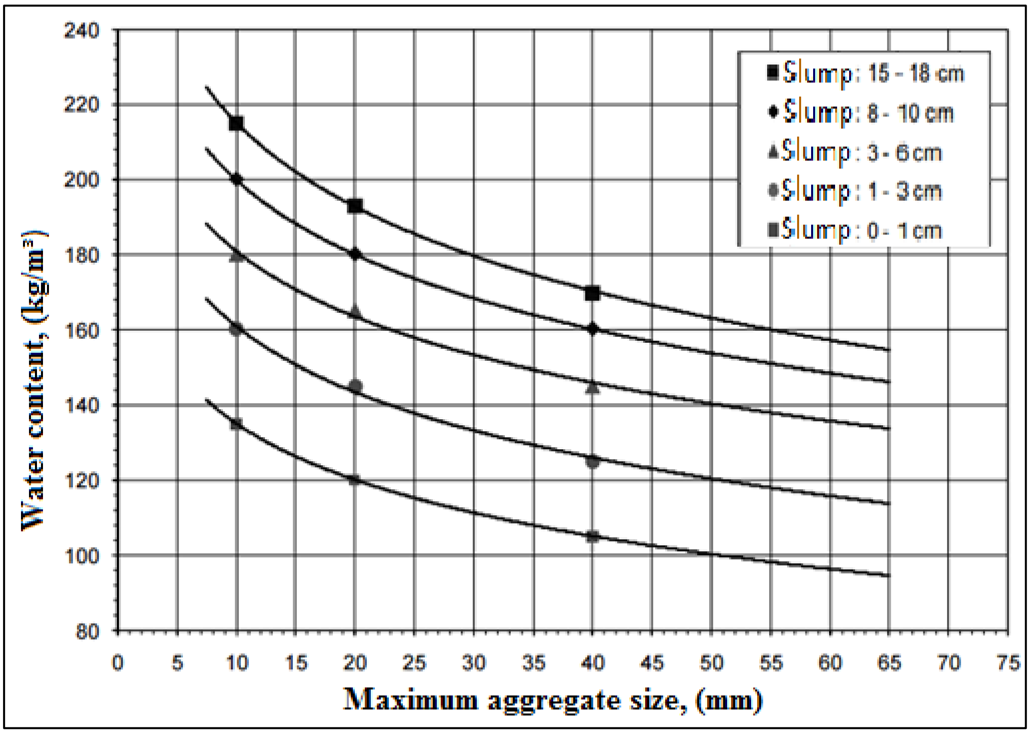


Figure 2.11. Mixing water for air-entrained concrete (TS 802, 2009)

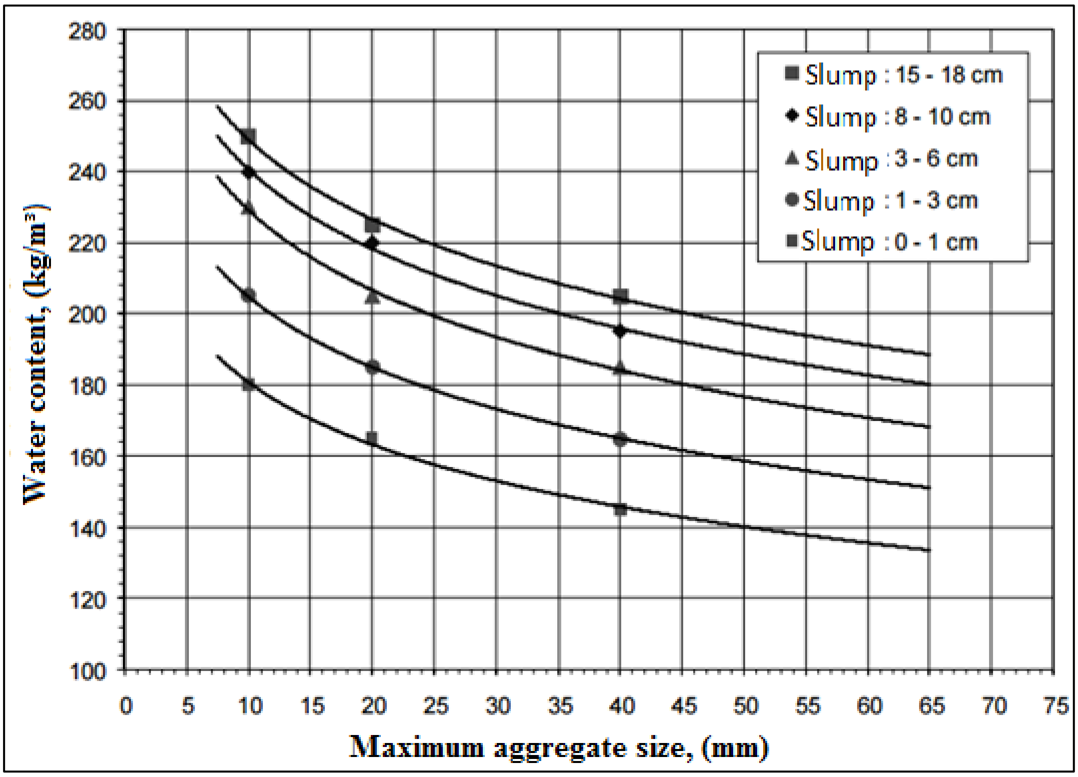


Figure 2.12. Mixing water for non-air-entrained concrete (TS 802, 2009)

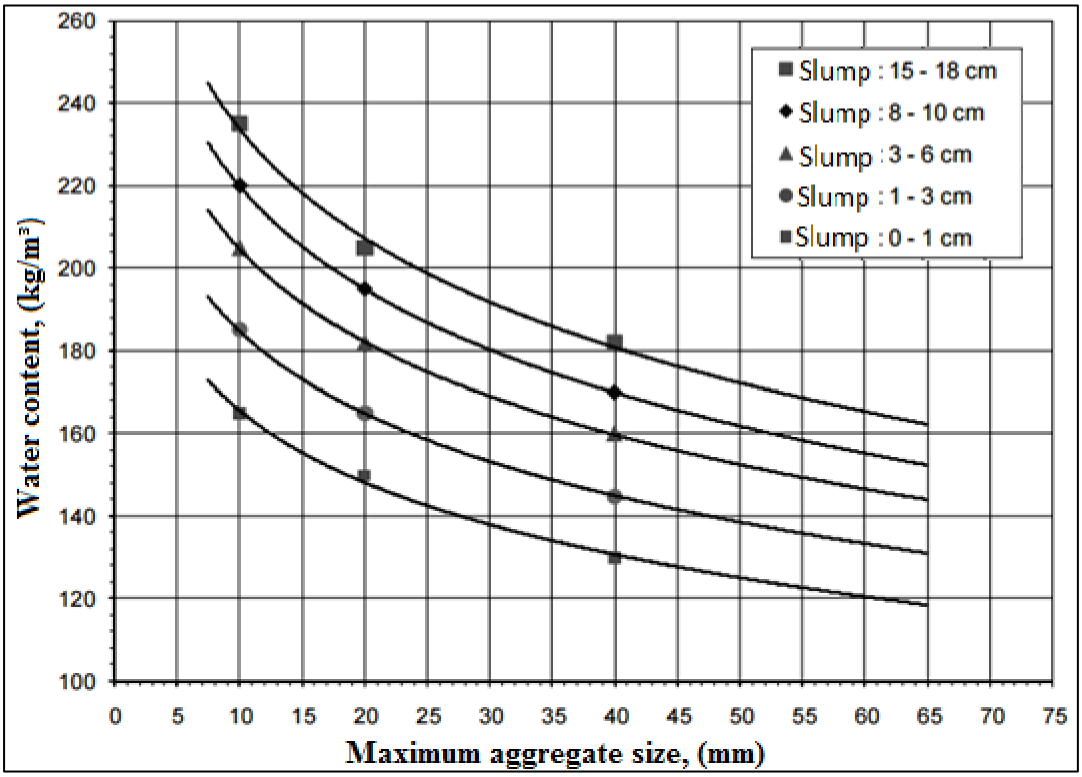


Figure 2.13. Mixing water for air-entrained concrete (TS 802, 2009)

2.3.1.5 Determination of Air Amount

The pores that emerge in case of incomplete compaction during the fresh state are called as air voids. These air voids have a negative effect on features of concrete. The amount of air in the concrete must be decided by considering the highest aggregate particle size as well as ambient conditions. Finally, graphs that are used to calculate the amount of air for both non-air-entrained and air-entrained concrete are illustrated in Figure 2.14.

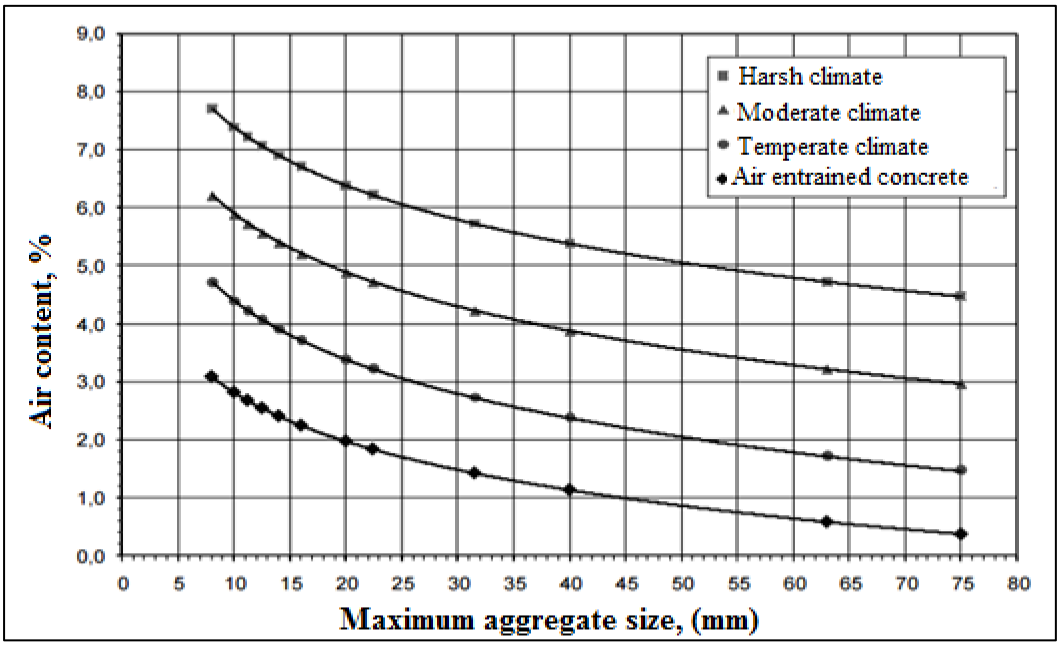


Figure 2.14. Air content in concrete mixture (TS 802, 2009)

2.3.1.6 Determination of Viscosity

Viscosity is known as resistance level of fresh concrete against flow. In other words, viscosity shows wetness level of the product and it is often determined by slump test. The viscosity might change due to the environmental conditions during the pouring stage. Due to the recent improvements in concrete technology and increasing chemical additives use, it is possible to transfer high viscosity concrete for pumps without losing stability and uniformity. In case the viscosity is not mentioned in a project, Table 2.6 could be used to determine appropriate slump values for various structural components.

Table 2. 6 Appropriate slump values for several structural elements (TS 802, 2009)

Structural component	Slump, (mm)	
	Minimum	Maximum
Concrete foundation walls and footings	30	80
Non-reinforced concrete foundations, caissons and sub-structure walls	30	80
Joist, column, concrete walls, tunnel segments	50	100
Slab concrete	30	80
Tunnel floor coating concrete	30	50
Dam mass concrete	20	50

2.3.1.7 Calculation of Mix Proportions

Following formula is used to calculate the amounts of materials used in 1 m^3 concrete:

$$\frac{ç}{\rho_ç} + \frac{p}{\rho_p} + \frac{k}{\rho_k} + w + \frac{W_a}{\rho_a} + 10 \times A = 1000 dm^3 \text{(Liter)}$$

Where;

ç: Mass of cement mass (kg) ,

p: Mass of mineral additive (pozzolana) (kg) ,

k: Mass of chemical additive (kg) ,

$\rho_ç$: Density of cement (kg/dm^3) ,

ρ_p: Density of mineral additive (kg/dm^3) ,

ρ_k: Density of chemical additive (kg/dm^3) ,

W: Volume of water (dm^3, liter),

W_a: Quantity of aggregate (kg),

ρ_a: Approximate density of aggregates (g/cm^3) or (kg/dm^3) ,

A: Total air content (%)

After deciding the water/cement ratio after step 3 and the required water amount in step 4, one can calculate the cement mass in the mixture using the formula below:

$$ç = \frac{s}{s/ç}$$

Where;

ç: Mass of cement (kg) ,

s: Mass of water (kg) ,

s/ç: Water-cement ratio

Next, in order to determine the aggregate volume and thus the aggregate quantity in the mixture the formula can be rewritten as follows:

$$V_a = \frac{W_a}{\rho_a} = 1000 - \left(\frac{ç}{\rho_ç} + \frac{p}{\rho_p} + \frac{k}{\rho_k} + s + A\right)(liter)$$

After finding the aggregate volume, the density of every particle class needs to be calculated in order to determine the aggregate mass to be used for 1 m3 of concrete and the average density of the aggregate to be used for the concrete mixture. For calculation the formula below is used:

$$\bar{\rho}_a = \frac{1}{\frac{x_1}{\rho_{a_1}} + \frac{x_2}{\rho_{a_2}} + \frac{x_3}{\rho_{a_3}} + \cdots + \frac{x_n}{\rho_{a_n}}}$$

Here;

ρa: The weighted average relative density value of the aggregate,

$x_1, x_2, x_3, \ldots, x_n$: The mixture proportions of various particle classes,

$\rho a_1, \rho a_2, \rho a_3, \ldots, \rho a_n$: Specific grawity of the aggregates.

Finally, the total mass of the aggregate for 1 m^3 of concrete can be found by using the formula below.

$$M_a = V_a x \bar{\rho}_a$$

2.3.1.8 Verification of the Mixture Calculation by Experiments

Suitable particle distribution value as well as the rate of water and water quantity are obtained from experimental results. Hence, a trial mixture should be prepared by using calculated values in order to verify calculated values. If there exists a difference between the characteristics of fresh and hardened concrete before and after experiment, it should be done again.

2.3.2 Concrete Mix Design Standard of American Concrete Institute (ACI)

American Concrete Institute (ACI) recommends a different but widely used method. The ACI method requires 9 steps illustrated in Figure 2.15.

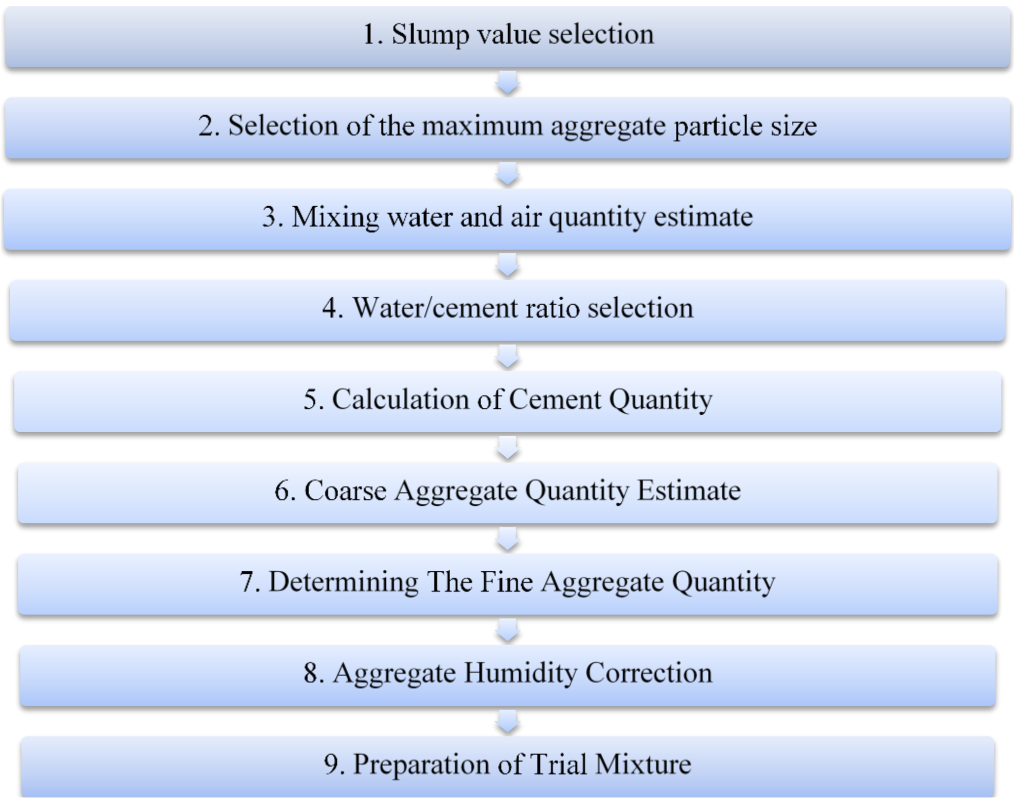


Figure 2. 15. The concrete mixture design according to ACI

2.3.2.1 Slump Value Calculation

The first step is deciding the slump value. Table 2.7 illustrates the values to determine the value. Besides, according to Mehta and Monteiro (2006), the concrete mixture's slump range should be between 100 -150 mm.

2.3.2.2 Selection of the Maximum Aggregate Particle Size

The quantity of pores as well as the quantity of mortar in concrete reduces as the maximum aggregate particle size increases. According to ACI standards the maximum aggregate particle size should not exceed 1/5 of the narrowest size between the form corners, 1/3 of the flooring depth and 3/4 of the minimum distance between the reinforcements (Mehta and Monteiro, 2006). Slump values according to various structure types are shown it the Table 2.7.

Table 2. 7 Determining slump value according to different structure types (ACI 211.1-91, 2006)

Structure Type	Slump Value (mm)	
	Maximum	Minimum
Reinforced Foundation Walls and Footings	75	25
Plain Footings, Caissons and Substructure Walls	75	25
Beams and Reinforced Walls	100	25
Columns	100	25
Coating and Flooring	75	25
Mass Concrete	50	25

2.3.2.3 Estimate of Mixing Water and Air Quantity

According to ACI standards, the amount of water for 1 m^3 of concrete is related to the greatest aggregate particle size, aggregate shape and classification, concrete temperature, entrained air amount and finally chemical additives. Although, the amount of water and air shown in Table 2.8 changes a little bit according to the type of aggregate and its classification, the amount of information is enough for the start.

Table 2. 8 Mixing water and air amount estimation (ACI 211,1-91, 2006)

Concrete Containing Non-Entrained Air								
Slump (mm)	Water quantity (kg/m³) fort he listed nominal maximum aggregate particle size (mm)							
	9,5	12,5	19	25	37,5	50	75	100
25-50	207	199	190	179	166	154	130	113
75-100	228	216	205	193	181	169	145	124
150-175	243	228	216	202	190	178	160	-
Air Quantity (%)	3	2,5	2	1,5	1	0,5	0,3	0,3
Air Entrained Concrete								
25-50	181	175	168	160	150	142	122	107
75-100	202	193	184	175	165	157	133	119
150-175	216	205	197	184	174	166	154	-
Recommended Air Content (percent)								
Mild Exposure	4,5	4,0	3,5	3,0	2,5	2,0	1,5	1,0
Moderate Exposure	6,0	5,5	5,0	4,5	4,5	4,0	3,5	3,0
Severe Exposure	7,5	7,0	6,0	6,0	5,5	5,0	4,5	4,0

2.3.2.4 Determination of Water to Cement (w/c) Ratio

The water-to cement ratio (w/c) or the rate of water binder (w/b) used in mixture has a direct effect on several features of concrete. However, it is not easy to find a relation between the compressive strength of concrete and w/c ratio. Therefore, the ratios given in Table 2.9 may be used in case these relations do not exist and cement doesn't contain mineral additives. Besides, durability instead of strength can be more important for some instances. In these cases, using ratios given in Table 2.10 is more appropriate.

Table 2. 9 Water to cement ratios and the pressure resistance (ACI 211,1-91, 2006)

28-Day Compressive Strength (MPa)	w/c ratio by weight	
	Non-air-entrained concrete	Air-entrained concrete
41.4	0.41	-
34.5	0.48	0.40
27.6	0.57	0.48
20.7	0.68	0.59
13.8	0.82	0.74

Table 2. 10 Maximum water to cement ratio in concrete subject to severe environmental conditions (ACI 211,1-91, 2006)

Structure Type	Concrete Which is Always Wet or Frequently Exposed to Freezing-Defreezing	Concrete Exposed to Sea Water or Sulphated Ambiance
Concrete which has thin section or less clear cover than 25	0.45	0.40
Other structures	0.50	0.45

2.3.2.5 Calculation of Cement Amount

The quantity of cement is calculated by dividing the amount of water determined in 2.3.2.3 part to the water/cement ratio.

2.3.2.6 Estimation of Coarse Aggregate Amount

There exists a negative correlation between the coarse aggregate amount and the cost of production. The aggregate volume in 1 m^3 of concrete can be determined according to the values given in Table 2.11. The calculation is done using the maximum aggregate particle size and the fineness module of the fine aggregate. Calculated volume is then multiplied by the dry loose unit weight and finally converted to coarse aggregate dry weight (Mehta and Monteiro, 2006).

Table 2. 11 Determining the volume of coarse aggregate in 1 m^3 Concrete (ACI 211.1-91, 2006)

Nominal Maximum Aggregate Size (mm)	Fine Aggregate Fineness Modulus			
	2.40	2.60	2.80	3.00
9.50	0.50	0.48	0.46	0.44
12.50	0.59	0.57	0.55	0.53
19.00	0.66	0.64	0.62	0.60
25.00	0.71	0.69	0.67	0.65
37.50	0.75	0.73	0.71	0.69
50.00	0.78	0.76	0.74	0.72

2.3.2.7 Determination of the Fine Aggregate Amount

After estimation of the coarse aggregate amount, one can determine the fine aggregate amount considering either the weight or volume. According to volume method, which is more common, the volume of water, air, cement and coarse aggregate is subtracted from the volume of 1 m^3 and the volume of fine aggregate is found. Finally, the weight of the fine aggregate calculated as multiplication of this value and density.

2.3.2.8 Aggregate Humidity Correction

In calculations, it is assumed that the aggregates are in saturated-surface dry status. But, aggregates may incur more or less humid compared to weather conditions. If the humidity correction is not made in such a case, the actual water-cement ratio of the trial mixture will be higher or lower than the water-cement ratio selected in part 2.3.2.4. It is important to note that the weights of coarse and fine aggregates that are calculated according to the equations described above (in parts of 2.3.2.6 and 2.3.2.7) are only for dry aggregate.

2.3.2.9 Preparation for Trial Mixture

Then, a nearly 20 dm^3 (liter) trial mixture needs to be prepared and go through the slump test during the concrete is fresh. One should also note that the unit weight and air amount of the fresh concrete needs to be measured. After taking the samples from the fresh concrete and curing for a period, a test should be conducted to determine compressive strength. After obtaining the desired serviceability and resistance after a couple of trials, the mixture ratios are ready to be used on site (Mehta and Monteiro, 2006)

2.4 Concrete Classes According Turkish Standards

Identified concrete classes and characteristic strengths according to Turkish Standards (TS 500, TS 11222, TS EN 206, TS 10465,) are shown in Table 2.12. Explanations of Turkish Standards are:

- **TS 500:** Turkish Standards: Design and construction rules of concrete structures.
- **TS EN 206:** Turkish Standards: Specification, performance, production and conformity standards.
- **TS 11222:** Turkish Standards: Ready mixed concrete standards.
- **TS 10465:** Turkish Standards: Test methods for concrete: sampling of hardened concrete and determination of compressive strength for structures and structural elements.

Table 2. 12 Concrete classes according to Turkish Standards

Strength Class of Concrete				Characteristic Strength f_{ck}							
				Cylindrical Concrete Specimens (15*30)cm				Concrete Cubic Specimens (15*15*15)cm/ (20*20*20)cm			
TS 500	TS EN 206	TS 11222	TS 10465	TS 500	TS EN 206	TS 11222	TS 10465	TS 500	TS EN 206	TS 11222	TS 10465
	C 8/10				8				10		
	C 12/15				12				15		
	-	C 14	BS 14		-	14	14		-	16	16
C 16	C 16/20	C 16	BS 16	16	16	16	16	20	20	20	20
C 18	-	C18	-	18	-	18	-	22	-	22	-
C 20	C 20/25	C 20	BS 20	20	20	20	20	25	25	25	25
C 25	C 25/30	C 25	BS 25	25	25	25	25	30	30	30	30
C 30	C 30/37	C 30	BS 30	30	30	30	30	37	37	37	35
C 35	C 35/45	C 35	BS 35	35	35	35	35	45	45	45	40
C 40	C 40/50	C 40	BS 40	40	40	40	40	50	50	50	45
C 45	C 45/55	C 45	BS 45	45	45	45	45	55	55	55	50
C 50	C 50/60	C 50	BS 50	50	50	50	50	60	60	60	55
	C 55/67	C 55			55	55			67	67	
	C 60/75	C 60			60	60			75	75	
	C 70/85	C 70			70	70			85	85	
	C 80/95	C 80			80	80			95	95	
	C 90/105	C 90			90	90			105	105	
	C 100/115	C 100			100	100			115	100	

2.5 Compressive Strength of Concrete

Compressive strength is known as the maximum stress that a solid material can sustain without fracture under a gradually applied load. Compressive strength of concrete is related to water to cement ratio, its strength and finally quality of material used are among these factors.

Compressive strength test could be done by using cube or cylinder specimens. According the standards of American Society for Testing Materials (ASTM C39/C39M), 15 cm by 30 cm and 10 cm by 20 cm cylinder specimens are used for determination of compressive strength of cylinders. In case cube is used for test, there exists to types as 15 cm or 10 cm.

The concrete then poured in the mould. And it is tempered properly to avoid any voids. After a 24 hour period moulds are replaced with test specimens for curing. In order to gain a smooth surface, cement paste should be spreaded on the area of specimen. Then they need to be tested on 7th and 28th days of curing. Load should be applied gradually at the rate of 140 kg/cm^2 per minute. The compressive strength of concrete is calculated by dividing the load during the failure time by original cross-sectional area.

2.6 Studies on Modeling Compressive Strength of Concrete

Mermerdaş et al. (2012) modeled compressive strength of metakaolin (MK) and calcined kaolins (CKs) modified concrete by means of gene expression programming (GEP). They indicated that GEP is a perfect tool for prediction of concrete's compressive strength. Their results which include comparison of predicted vs. actual compressive strength values are indicated in Figure 2.16.

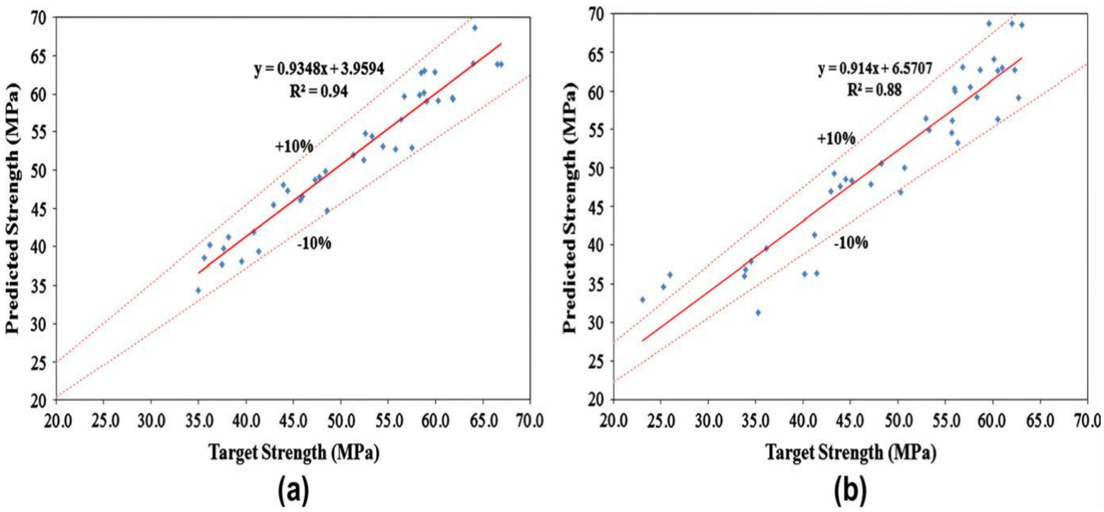


Figure 2. 16. Predicted vs. experimental values; (a) train data set, (b) test data set (Mermerdaş et al., 2012)

Sayed (2012) investigated the predictability of compressive strength of concrete containing different matrix mixtures by using statistical modeling methods. Eight different parameters: age, water, cement, metakaolin (MK), silica fume (SF), sand, aggregate and super plasticizer (SP) was used for this investigation. According to his findings, statistical modelings are capable for predicting concrete’s compressive strength. Results are illustrated in Figure 2.17.

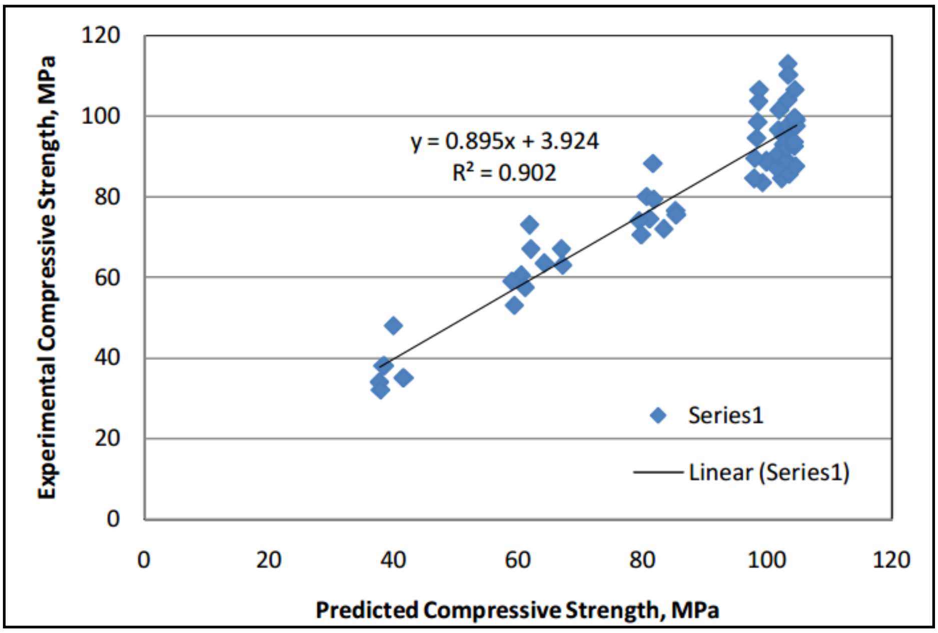


Figure 2. 17. Experimental results vs. predicted results of concrete’s compressive strength (Sayed, 2012)

Deshpande et al. (2014) used 3 different data driven techniques namely artificial neural networks (ANN), model tree (MT) and non-linear regression (NLR) to guess the 28 day compressive strength of recycled aggregate concrete (RAC). Their study indicated that with 9 input parameters (minimum mandatory amount), ANN predicts compressive strength of RAC better than MT and NLR. However, MT and NLR techniques have advantageous aspects: MT technique could build a family of models of different complexity and accuracy, and NLR technique could build a single equation which can be readily used. Result of their study is shown in Figure 2.18.

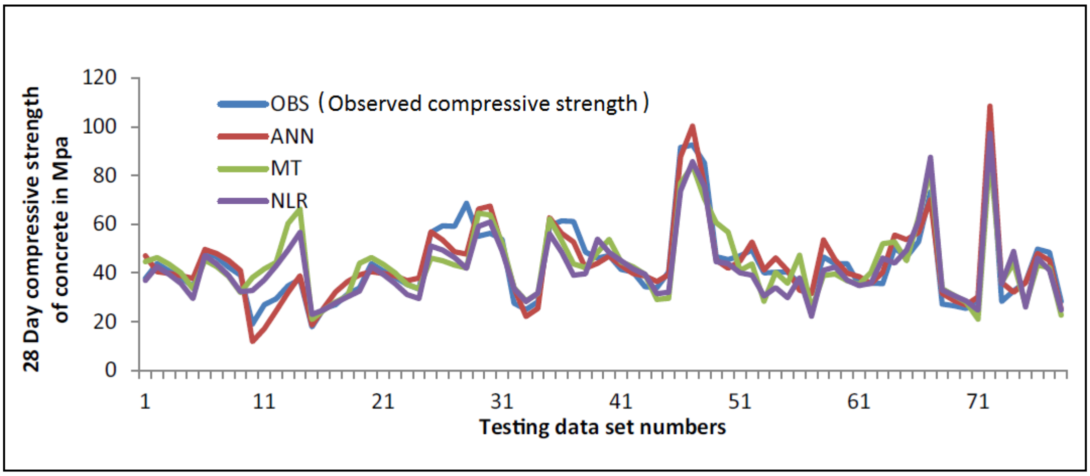


Figure 2. 18. Test and observation values for ANN10, MT10 and NLR10 (Deshpande et al., 2014)

Chandwani et al. (2014) conducted a study to model compressive strength of self compacting concrete (SCC), high performance concrete (HPC), and RAC by using ANN. They used non-destructive test data for the modeling. According to their study, the ANN is an effective technique that can be used as a predicting tool based on previous data, to guess the compressive strength of different types of concretes based on mix proportions.

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Materials

CEM II 32.5, CEM I 42.5, and CEM I 52.5 class cements with specific gravity of 3.05, 3.14, and 3.15, respectively, which are confirming Turkish Standard requirements, were utilized in the production of concrete mixtures. Physical features as well as chemical compositions are given in Table 3.1

Table 3.1 Chemical compositions and some physical properties of CEM I-52.5, CEM I-42.5, and CEM II-32.5

Item	CEM I 52.5	CEM I 42.5R	CEM II 32.5
SiO_2 (%)	18.22	18.99	20.31
Al_2O_3 (%)	63.85	3.95	4.96
Fe_2O_3 (%)	3.45	4.65	2.9
CaO (%)	3.65	62.76	60.48
MgO (%)	1.55	2.32	1.65
SO_3 (%)	2.72	2.75	2.51
Na_2O (%)	-	-	0.26
K_2O (%)	0.2	-	0.6
Cl^- (%)	0.005	0.0063	0.01
Insoluble residue	0.26	0.34	3.2
Loss on ignition	1.43	0.87	6.3
Free lime (%)	0.78	1.68	-
Specific gravity	3.15	3.14	3.05
Le chatelier (mm)	1	1	1
Blaine surface area (cm^2/g)	4,680	3,520	3,750

The medium and coarse aggregate was river gravel with a nominal maximum size of 16 mm and 22.5 mm, respectively. The gravities of natural sand, medium, and coarse aggregates are 2.65, 2.43, and 2.71, respectively. Particle size gradation is illustrate in Figure, 3.1.

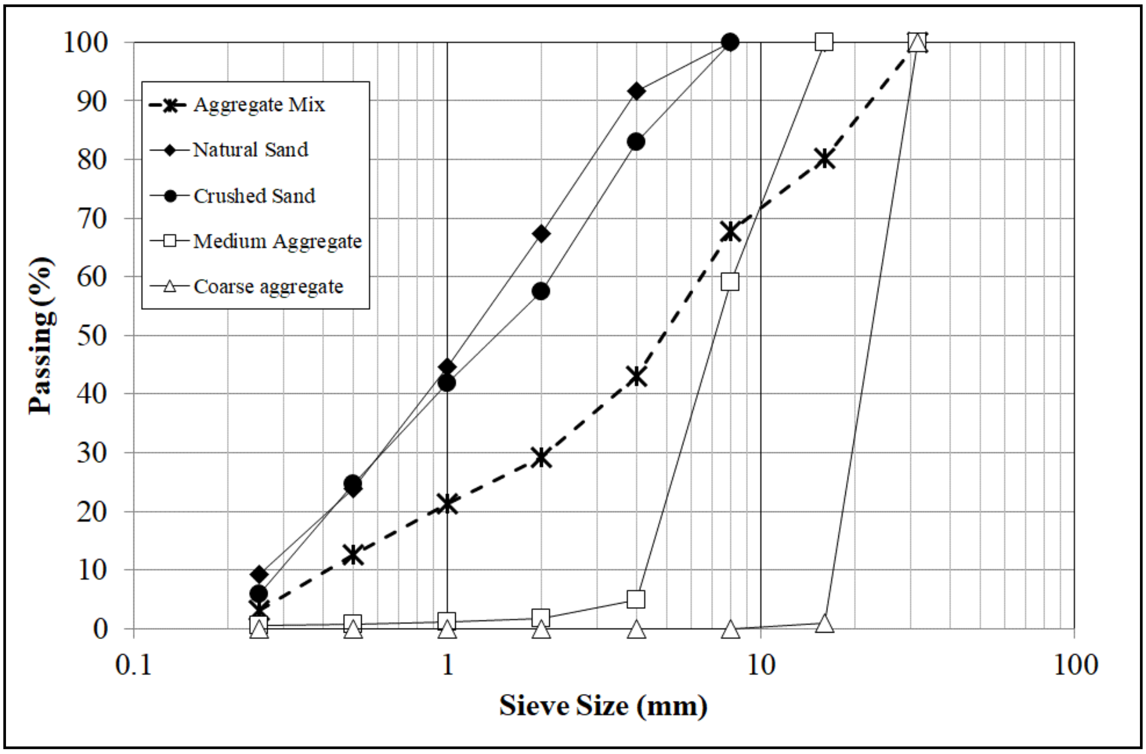


Figure 3.1. Distribution of the aggregates according to particle size

3.2 Mixture Design

The concrete mixtures were grouped in three according to the cement type utilized in the production of concrete. In each group, the concrete mixtures were manufactured considering various cement contents and water/cement ratios. Totally 36 concrete 7 and 28-day compressive strengths of cements were 32.5, 42.5, and 52.5 MPa confirming Turkish Standard. The water/cement ratio was determined as 0.3, 0.4, 0.5, and 0.6 and cement content as 300, 400, and 500 kg/m3. As results, in each group, twelve concrete mixtures were designed and totally, thirty six different concrete mixtures were manufactured in this study. The detailed mix proportions of the concrete mixtures are presented in Table 3.2

Table 3.2 Mix proportions for 1 m^3 concrete (in kg/m^3)

Cement content (kg/m^3)	Water-to-cement ratio (w/c)	Proportions of Aggregates (Coarse/Medium/Natural)
300 400 500	0.3 0.4 0.5 0.6	0.2/0.3/0.5

3.3 Concrete Casting

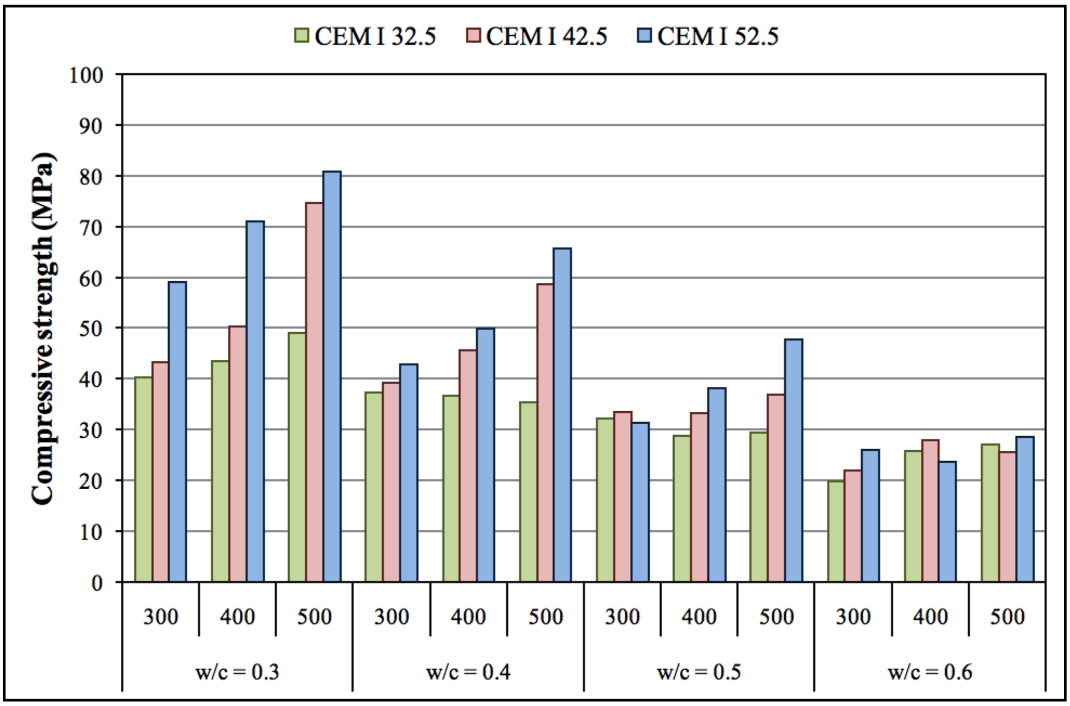
The same batching and mixing procedure needs to be followed to reach the same homogeneity and uniformity level. The mixtures were prepared by using a revolving pan mixer. After the production process, fresh mixtures were poured into the moulds. Then, all specimens were covered and left in the casting room for 24 h at 20±2 °C before they were demolded and 7-day and 28-day. Afterwards, they were tested based on the testing procedure proposed ASTM C39 (ASTM Standards, 2012) to determine concrete's compressive strength.

CHAPTER 4
EXPERIMENTAL RESULTS

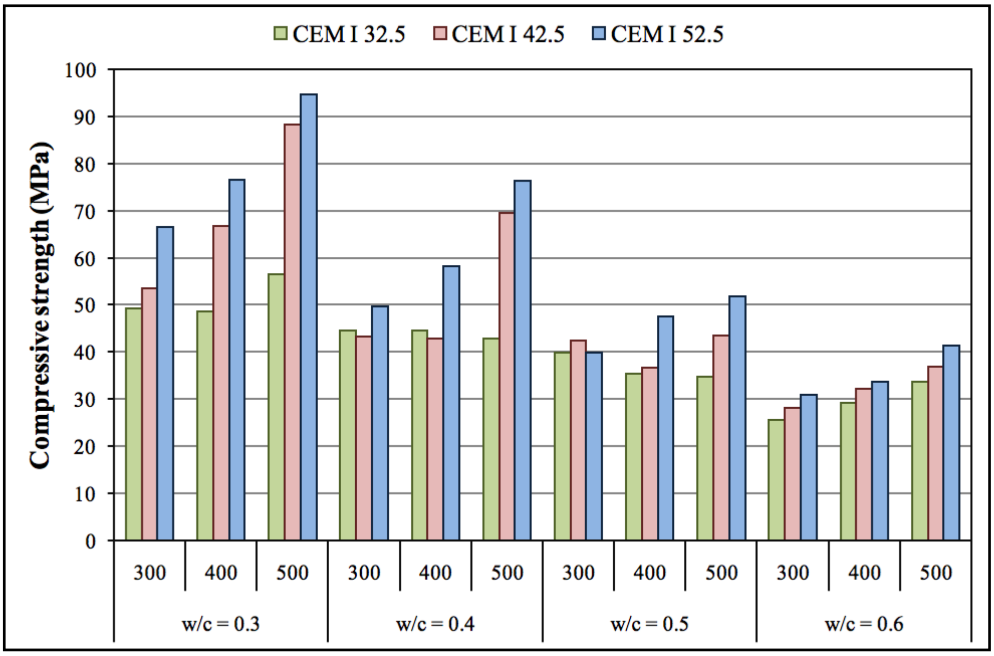
The compressive strength results of the mixtures at 7 and 28 days regarding to cement content and water/cement ratio with using different cement types are given in Table 4.1 and the data provided in this table were used in plotting of Figure 4.a and 4.b, respectively, for the evaluation and discussion of the test results. The compressive strength values range between 19.8 and 80.8 MPa on 7th day and between 25.5 and 94.6 MPa on 28th day. The results indicated that compressive strength of concrete is directly affected by the cement type. The best performance was obtained in the concrete mixtures produced with CEM I 52.5 cement type. Utilization of higher strength cement in the production of concrete improved the cement paste of the hardened concrete that is the reason of achieving higher compressive strength. The water/cement ratio had significant influences on the compressive strength, by the way increasing the water/cement ratio from 0.3 to 0.6 resulted in systematically reducing in the compressive strength values at both testing ages. The lowest compressive strength values were obtained in the mixtures produced at water/cement ratio of 0.6, the almost all values were under 40 MPa. The results also indicated that there is no significant change in compressive strength of the concrete mixtures produced with CEM II 32.5 type of cement when the cement content is increased from 300 to 500 kg/m3. At both testing ages, the cement content increasing in the mixtures manufactured with CEM II 32.5 type of cement increased just the compressive strength of the concrete produced with water/cement ratio of 0.6 while in the others no remarkable effect was observed. On the other hand, the influence of cement content on the compressive strength was clearly observed in the concrete mixtures produced with CEM I 52.5 type of cement. Increasing the cement content resulted in increment of compressive strength especially at lower water/cement ratios.

Table 4.1 Compressive strength of the concretes

Cement content (kg/m³)	w/c	Cement type	fc (MPa) 7-day	fc (MPa) 28-day	Cement type	fc (MPa) 7-day	fc (MPa) 28-day	Cement type	fc (MPa) 7-day	fc (MPa) 28-day
300	0.3	CEM I 52.5	59.1	66.6	CEM I 42.5	43.3	53.5	CEM II 32.5	40.2	49.3
	0.4		42.8	49.7		39.2	43.2		37.3	44.6
	0.5		31.4	40.0		33.5	42.5		32.1	39.9
	0.6		26.0	30.9		22.0	28.0		19.8	25.5
400	0.3		70.9	76.5		50.2	66.8		43.5	48.6
	0.4		49.8	58.2		45.5	42.8		36.7	44.6
	0.5		38.0	47.5		33.2	36.7		28.8	35.5
	0.6		23.7	33.6		27.8	32.3		25.8	29.3
500	0.3		80.8	94.6		74.6	88.3		48.9	56.4
	0.4		65.7	76.3		58.6	69.6		35.4	42.9
	0.5		47.8	51.7		36.8	43.6		29.3	34.8
	0.6		28.5	41.4		25.5	36.8		27.0	33.6



(a)



(b)

Figure 4. Compressive strength of the concrete mixtures versus water/cement ratio and cement content at: a) 7-day and b) 28-day

Reducing the water/cement ratio from 0.6 to 0.3 enhanced the compressive strength performance. For example, in the concrete series produced with CEM I 52.5 type of cement, the 7th day compressive strength values of concretes produced at 300, 400, and 500 kg/m3 of cement content augmented about 127.3%, 199.0%, and 183.2%, respectively, when water/cement ratio is decreased from 0.6 to 0.3. The increment rates in the 28th day compressive strength are 115.4%, 127.6%, and 128.7% for the same concretes. When the water/cement ratio of the concretes was decreased from 0.6 to 0.3, in the concrete series obtained by utilization of cement type of CEM I 42.5 and CEM II 32.5, the increment rates of the 7th day compressive strengths of the concretes manufactured with 300, 400, and 500 kg/m3 of cement content were, respectively, 96.8%, 80.6%, and 192.6% and 103.0%, 68.4%, and 81.1% whereas they were, respectively, 90.8%, 106.8%, and 140.0% and 93.3%, 66.1%, and 67.9% for the 28th day compressive strength.

Also, compressive strength of the concrete mixtures versus water/cement ratio and cement content at in Figure 4.a and 4.b respectively. It can be clearly observed from the figures, the compressive strength of the concretes is increased by augmenting of the aggregate-to-cement ratio.

CHAPTER 5

STATISTICAL EVALUATION AND MULTIPLE LINEAR REGRESSION (MLR)

Analysis of variance (ANOVA) is used to determine the relationship between dependent and independent variables. General linear model analysis of variance (GLM-ANOVA), an important statistical analysis and diagnostic tool, is based on reducing the control variance that helping to quantify the dominance of the control factor. The identification of the statistically significant experimental parameters on compressive strength was determined by analysis at 0.05 level of significance. The GLM-ANOVA technique by means of software called “Minitab” was used to examine the data given in Table 5. In this study, compressive strength is the dependent variable, while water/cement ratio, cement content, and cement compressive strength namely cement type are independent variables. The general linear model analysis was used to determine the effectiveness of the test parameters. Table 5 illustrates the statistical analysis results. The significance of the test parameter on the compressive strength is determined by the p-values. The parameter is acceptable as significant factor on the test result in the case of p-value of less than 0.05. According to the analysis results all parameters have a statistically significant influence on 7-day and 28-day compressive strengths of concretes (Table 5). Table 5 also illustrate the contributions of the factors on test results. Observing the contribution levels of independent variables indicated that the most important parameter in compressive strength is water/cement ratio at both testing ages. According to results, the contribution of cement compressive strength, namely cement type, and cement content is significantly low compared to contribution of water/cement ratio.

Table 5. Statistical evaluation of the compressive strength of the concretes

Dependent Variable	Independent variable	Sequential Sum of Squares	Computed F	P Value	Significance	Contribution (%)
7-day compressive strength	f_{cc}	1064.38	11.90	0.000	Yes	13.05
	w/c	5088.69	37.93	0.000	Yes	62.41
	c	748.08	8.36	0.001	Yes	9.18
	Error	1252.31	-	-	-	15.36
	Total	8153.43	-	-	-	-
28-day compressive strength	f_{cc}	1383.8	12.95	0.000	Yes	13.96
	w/c	5927.3	36.97	0.000	Yes	59.80
	c	1104.4	10.33	0.000	Yes	11.14
	Error	1496.3	-	-	-	15.10
	Total	9911.8	-	-	-	-

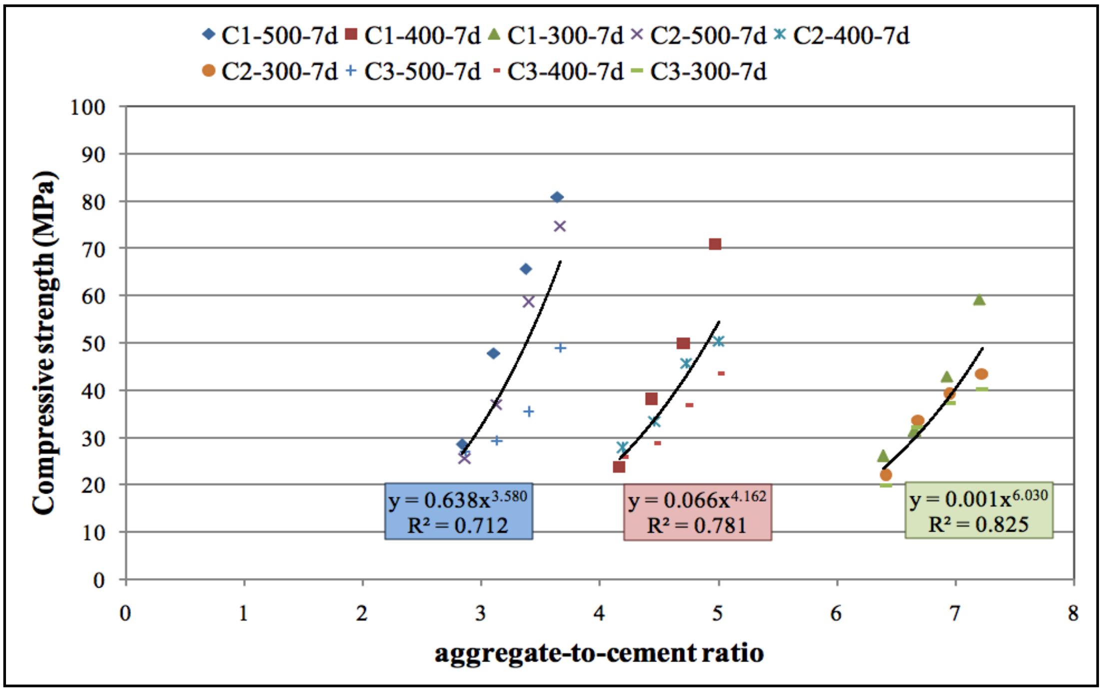
f_{cc}: compressive strength of cement; w/c: water/cement ratio; c: cement content

Moreover, by using Minitab, a linear equation of observed data was obtained by using multiple linear regression that modeling the relationship between a response variable and two or more descriptor variables.

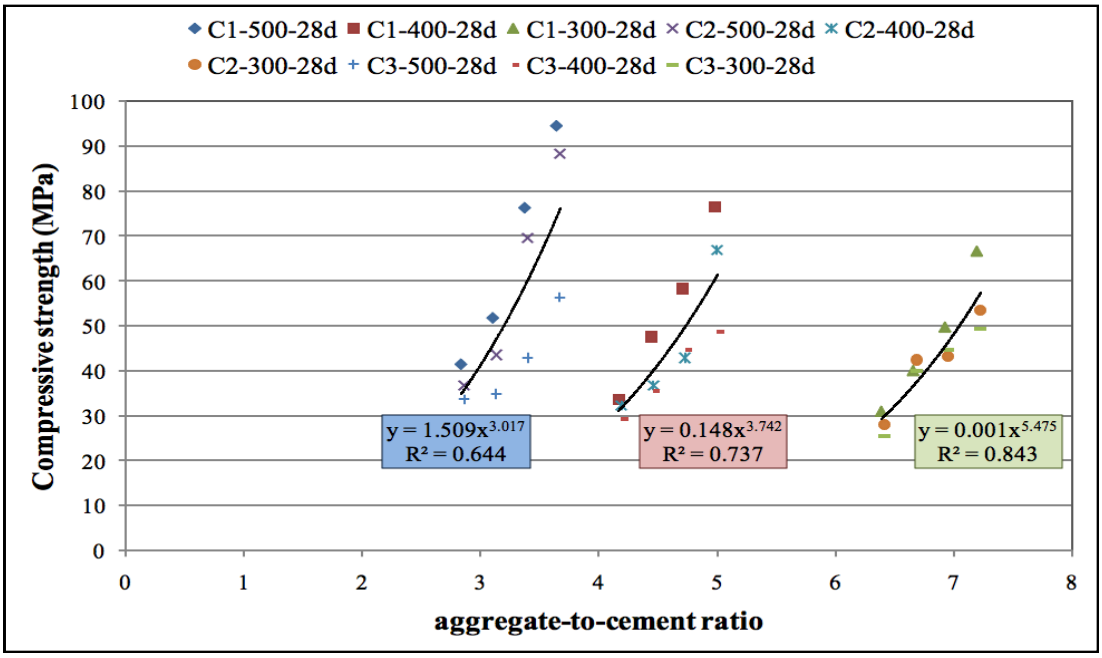
$$F_c = 77.03 + 0.7074 \times f_c - 118.81 \times w - 3.202 \times a + 0.3657 \times t \quad (1)$$

Where Fc is the compressive strength of the concrete, fc, w, a, and t are the compressive strength of the cement, water/cement ratio, aggregate-to-cement ratio, and testing age, respectively.

In addition, the results at 7 and 28 days are plotted with respect to compressive strength and aggregate-to-cement ratio on Figure 5.a and 5.b, respectively. Then, compressive strength results at each testing age were grouped into three according to cement content utilized in the production. Power function fitting was applied on each group. R-square values and power function equations for each group are also illustrated in Figure 5.a and 5.b According to the results, the higher R-square values of 0.825 and 0.843 was achieved in the concretes produced with 300 kg/m3 cement content at both ages.



(a)



(b)

Figure 5. Compressive strength values versus aggregate-to-cement ratio with power function fitting at: a) 7-day and b) 28-day

CHAPTER 6

DERIVATION OF PREDICTION MODEL

Gene expression programming, found out by Ferreira (2001), is a new technique to create computer programs by expression of the learned models or discovered knowledge (Li et al., 2005). Because gene expression programming is introducing genetic variation by using one or more genetic operators as genetic programming (GP) and genetic algorithms (GAs) and utilizing the populations of individuals by choosing them according to form, it is also a genetic algorithm. GP, proposed by Koza (1992), is a generalization of Gas (Gen and Cheng, 1997). Solving defined problem by employing a computer program is widely used. The definition of the problem is the first step in the logic of GP and GAs, and then the program tries to solve the problem in a problem-independent mode (Koza, 1992; Gen and Cheng, 1997). GEP is derived and enhanced form of GAs and GP. These three algorithms use almost same genetic operators in the solutions with minor changes.

The compressive strength of the cements, water/cement ratios, aggregate-to-cement ratios, and testing ages of concretes with experimental results were regulated to achieve a data set. Table 4.1 presents the data set which was randomly divided into two groups. “Train set” is one of the sub-data set whereas “Test set” is the other. The mathematical model was derived by using a software named GeneXproTools 4.0. The following expression is the prediction model that was achieved from GEP. The expression tree of the prediction model is also presented in Figure 6. The parameters used for the prediction model in GEP algorithm are given in Table 6.

Table 6. GEP parameters used for the proposed model

P1	Function set	+,-,*,/, Sin, Cos, Tan, Arccos, Arctan, Ln, Log, Sqrt, 3Rt, X2, X3, Exp, Inv Pow
P2	Number of generation	354711
P3	Chromosomes	30
P4	Head size	10
P5	Linking function	Addition
P6	Number of genes	6
P7	Mutation rate	0.044
P8	Inversion rate	0.1
P9	One-point recombination rate	0.3
P10	Two-point recombination rate	0.3
P11	Gene recombination rate	0.1
P12	Gene transposition rate	0.1
P13	Constants per gene	2
P14	Lower/Upper bound of constants	-10/10

$$F_c = F_1 + F_2 + F_3 + F_4 + F_5 + F_6 \quad (2)$$

$$F_1 = \arccos(\sin d_2) - \tan\left(\sqrt{d_1}\right) - d_0 \times \ln d_1 - 2 \times d_2 \quad (2a)$$

$$F_2 = \sqrt[3]{d_2 - \left(e^{c7}\right)^{\ln d_1}} \times \tan\left(\tan d_0^2\right) \quad (2b)$$

c_7 =-1.6339

$$F_3 = c_1 + \frac{\sqrt{d_1} \times \log d_3 \times \left(\arccos d_1 + c_5\right)}{d_1} \quad (2c)$$

c_1 = 0.3216, c_5 = 5.3928

$$F_4 = \frac{\sqrt[3]{c_7 \times d_2}}{d_1} \times \sin\left(\left(c_3 - d_2\right) \times \sqrt{c_9}\right) \quad (2d)$$

c_3 = -6.5469, c_7 = 1.6151, c_9=5.384

$$F_5 = c_2 - d_1 - \arctan\left(\tan d_0 \times \ln d_1 \times \left(c_6 + d_2\right)\right) \quad (2e)$$

$c_2 = 6.2143$, $c_6 = - 4.1084$

$$F_6 = \sin\left(\left(\tan d_0^2 + \cos e^{d_3}\right) \times d_0 \times \left(c_6 - d_2\right)\right)$$
(2f)

$c_6 =-9.6818$

Where Fc is the compressive strength of concrete, d0, d1, d2, and d3 are the compressive strength of the cement, water/cement ratio, aggregate-to-cement ratio, and testing age, respectively.

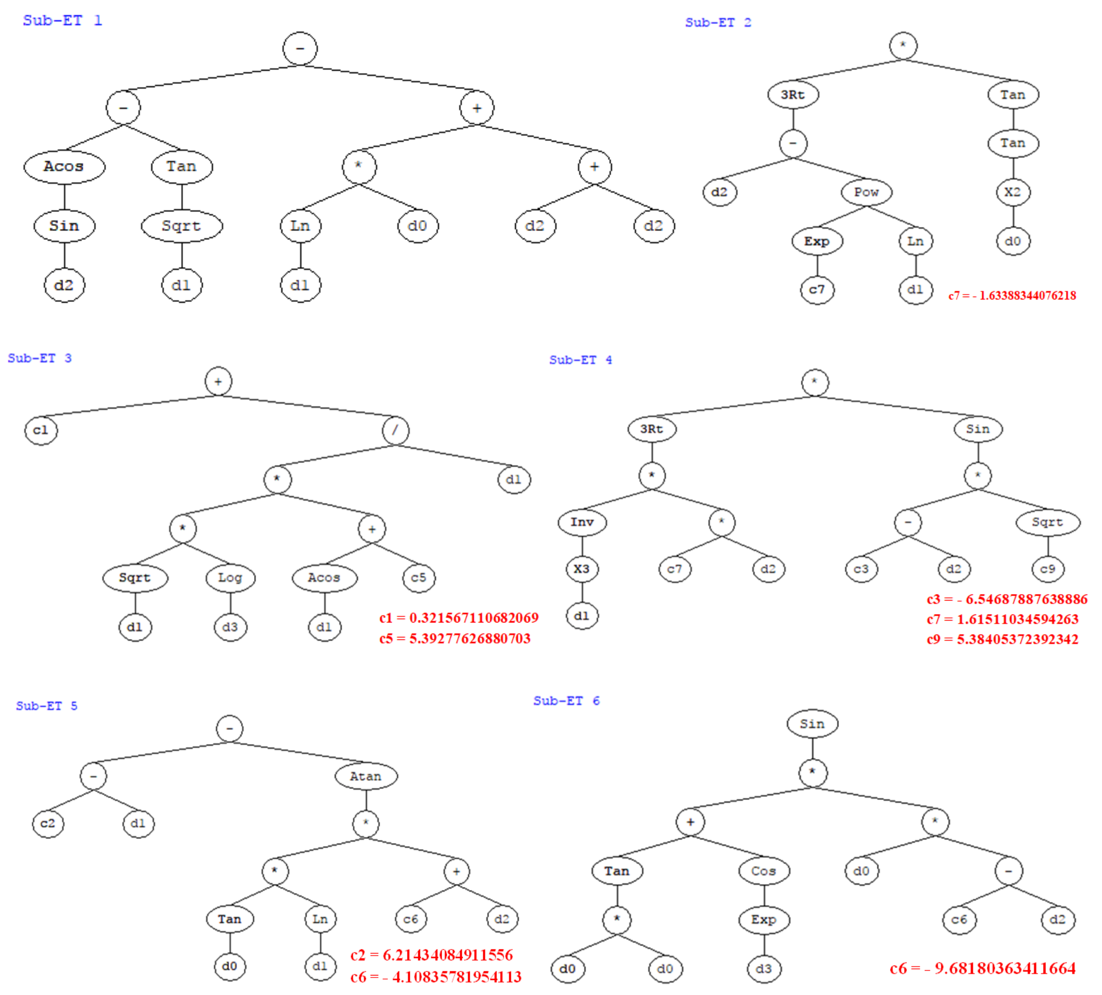


Figure 6. Expression trees for GEP model

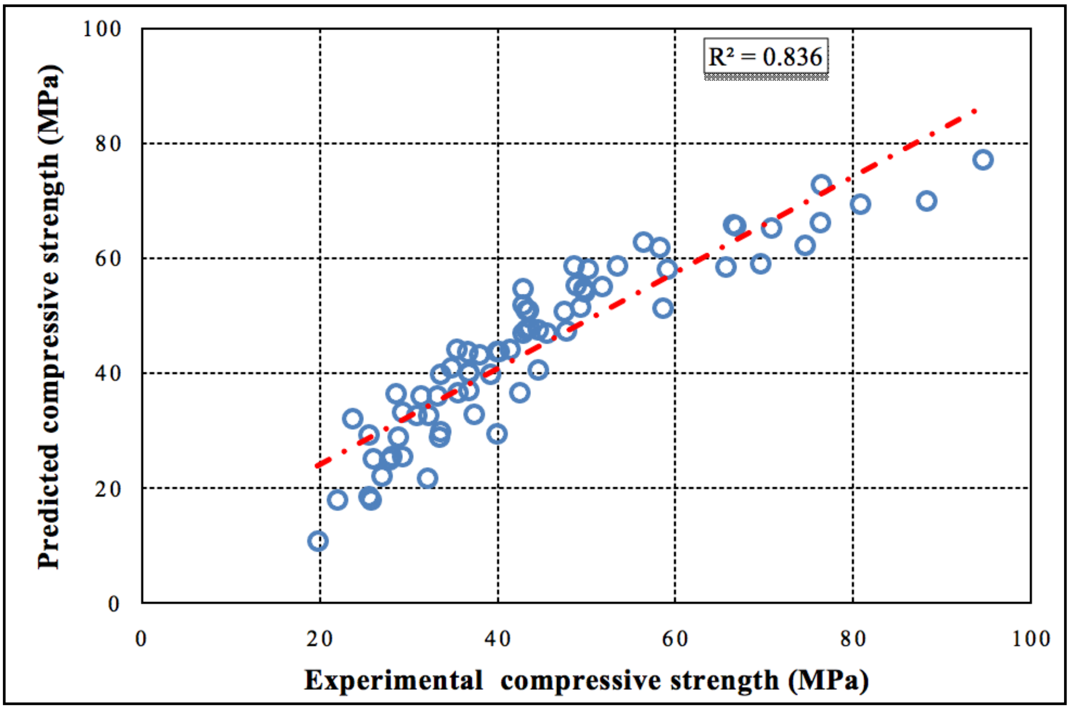
CHAPTER 7

CORRELATION BETWEEN PREDICTED AND EXPERIMENTAL COMPRESSIVE STRENGTH

Findings of the experiment could be assessed by using the correlation. To find the compressive strength of the mixtures, the predicted compressive strength is correlated with experimental values. The correlation between experimental and the one obtained by Multiple Linear Regregression (MLR) and another one predicted by mathematical model generated by GEP are presented in Figure 7.a and 7.b, respectively. The figures also illustrate the calculated correlation coefficients. As it is seen in results we found a strong correlation between the predicted and experimental compressive strength both for MLR and GEP. But the correlation coefficient of GEP model was higher than that of MLR model. The R2 value of the model proposed by GEP was about 0.955 while it was 0.836 for model obtained by MLR.

In addition to correlation, the experimental compressive strength values and predicted values are presented in Figure 7.1 By this plotting, it was aimed to see that the results achieved by GEP model gave better results than MLR model.

Then, we normalized the values of both MLR and GEP model to compare predicted and experimental results. Normalized values versus aggregate/cement ratio, cement strength, water/cement ratio, finally testing age are shown in Figure 7.2.a, 7.2.b, 7.2.c, and 7.2.d. According to the figures almost all GEP model data are dispersed in ±20% limit of the normal line whereas some data of MLP model are out of this limit. Hence, one can conclude that GEP model has a better performance.



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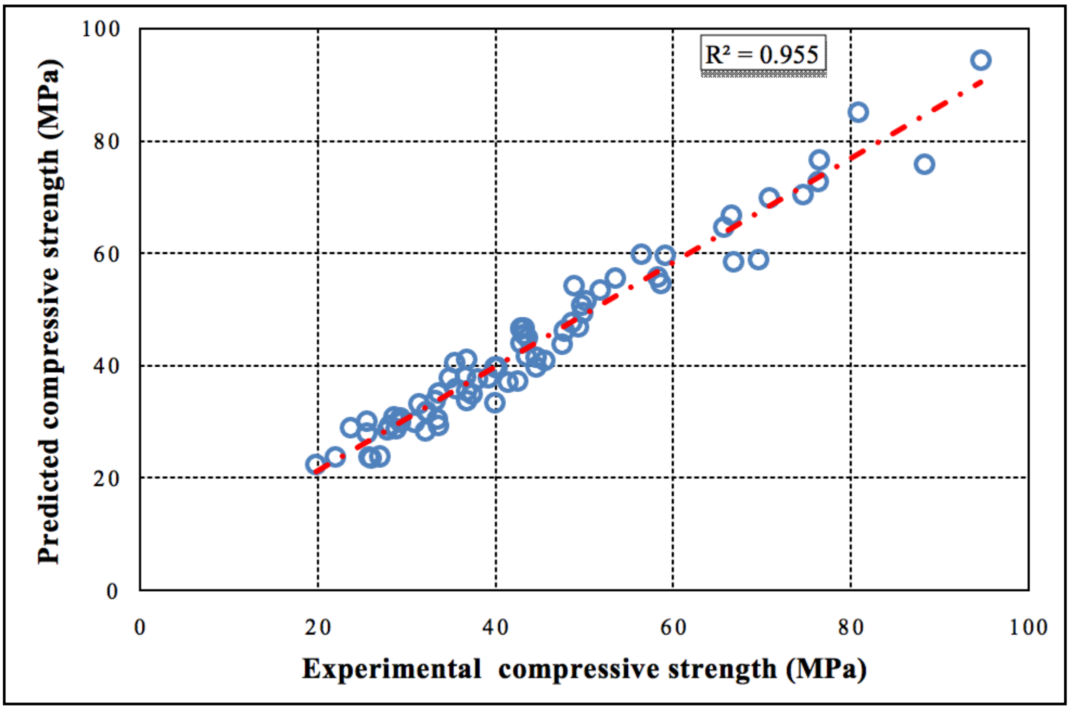


(b)

Figure 7. Predicted versus experimental compressive strength values for a) MLR and b) GEP models

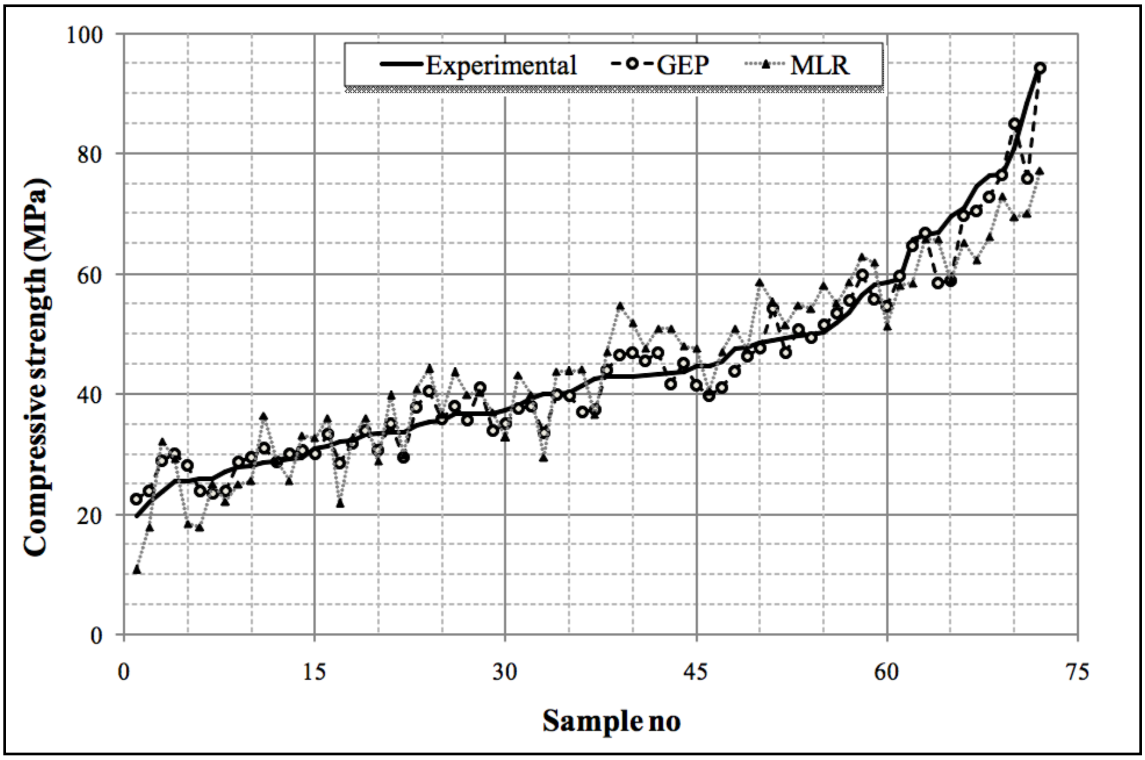
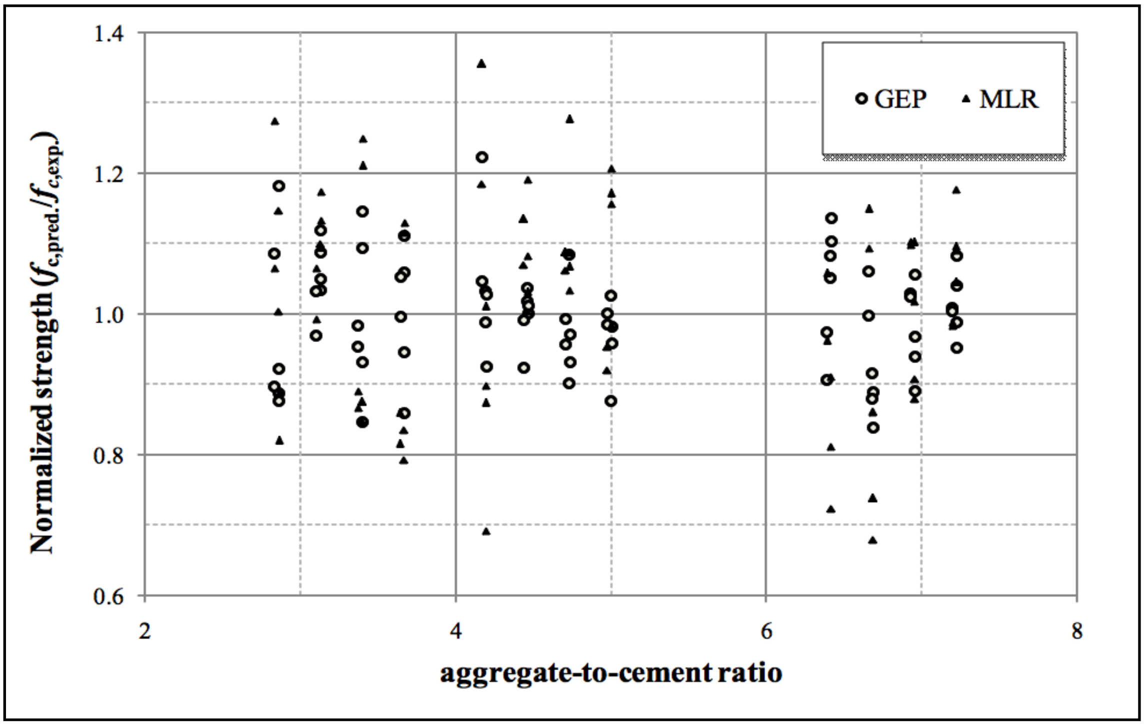
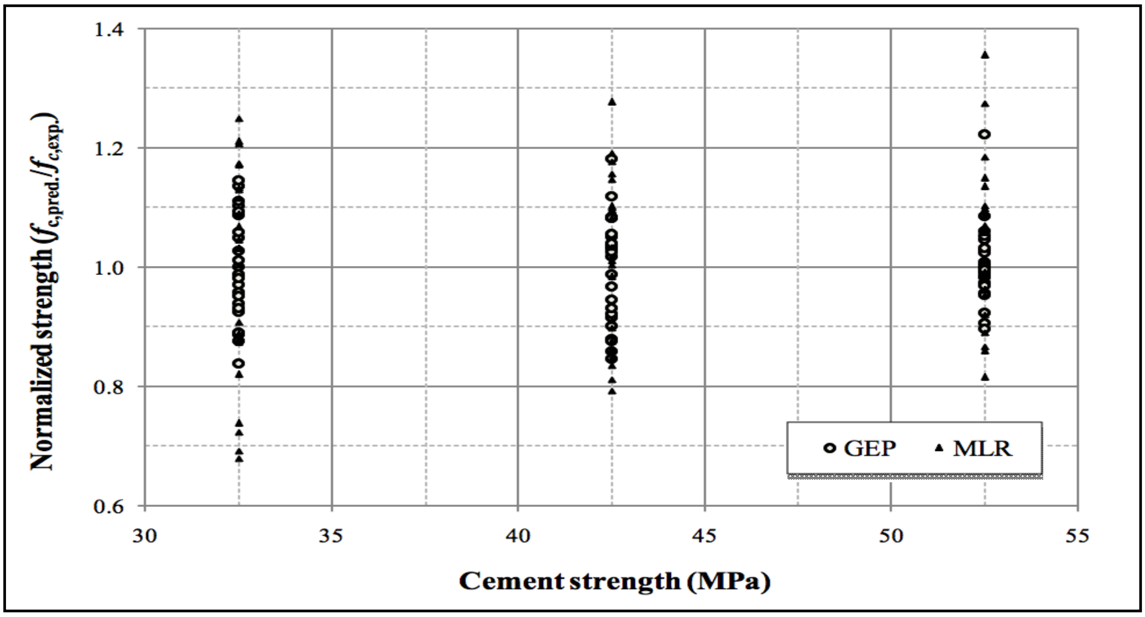


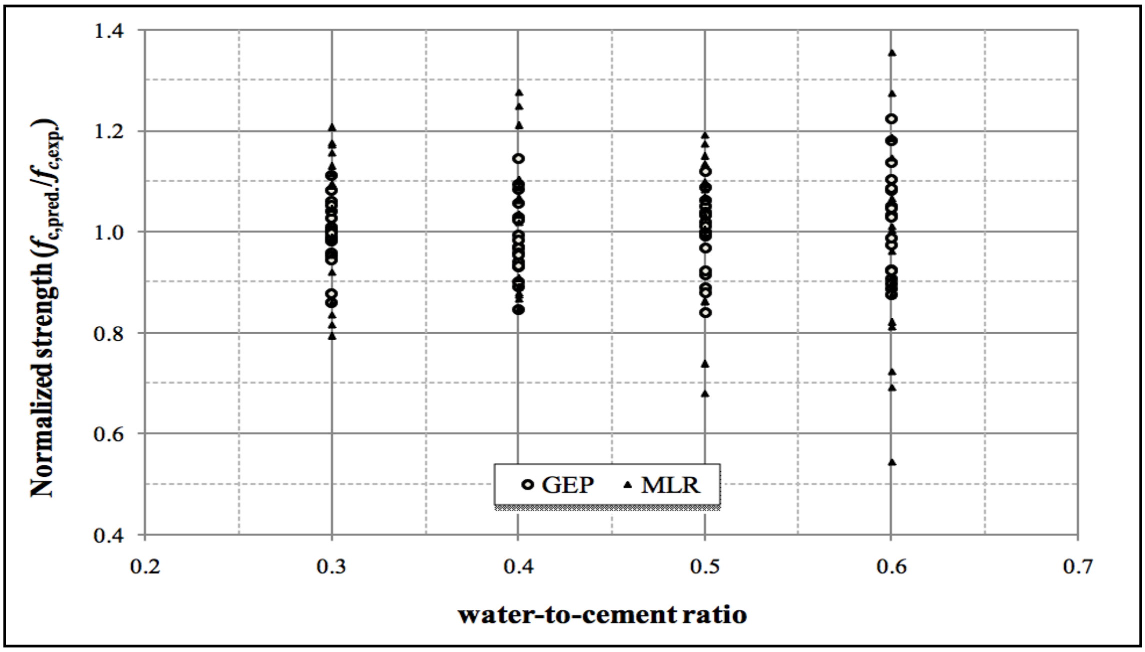
Figure 7.1. Compressive strengths predicted by MLR and GEP models and experimental compressive strength values versus number of sample



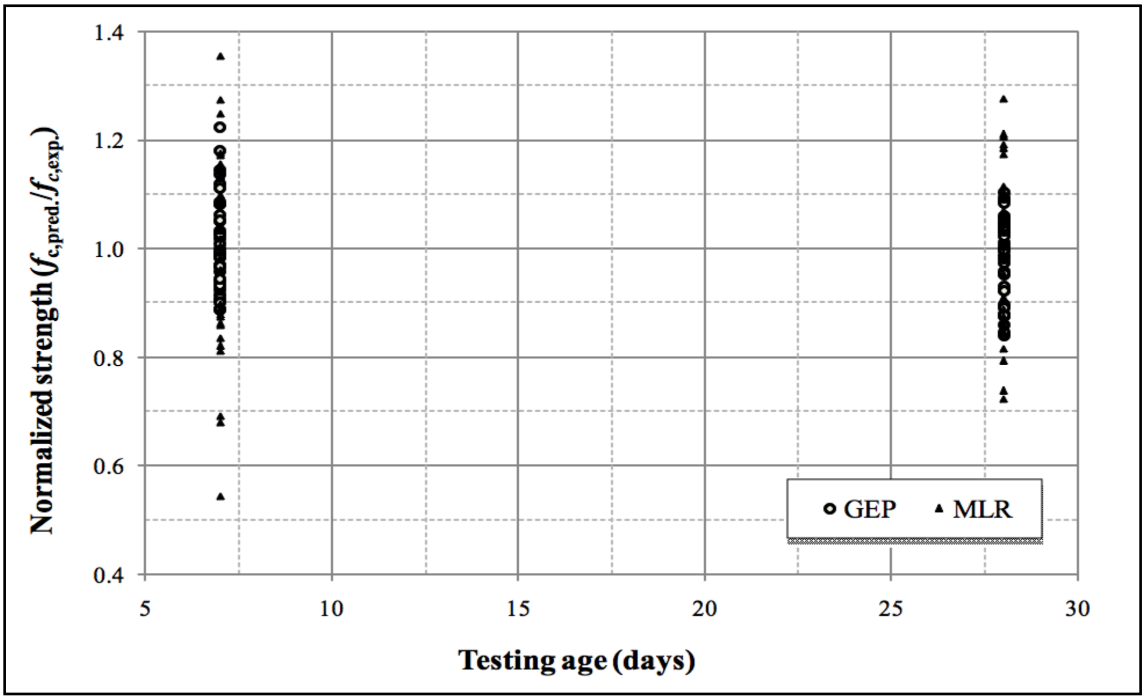
(a)


Normalized strength ($f_{c,pred.}/f_{c,exp.}$)
1.4
1.2
1.0
0.8
0.6
30
35
40
45
50
55
Cement strength (MPa)
GEP
MLR

(b)


Normalized strength ($f_{c,pred.}/f_{c,exp.}$)
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.3
0.4
0.5
0.6
0.7
water-to-cement ratio
GEP
MLR

(c)



(d)

Figure 7.2. Prediction performance of the GEP model with respect to: a) aggregate-to-cement ratio, b) cement strength, c) water/cement ratio, and d) testing age

CHAPTER 8

CONCLUSION

Finally, conclusions are listed below according to the findings of experimental study;

- Decreasing the water/cement ratio from 0.6 to 0.3 enhanced the compressive strength performance in all concrete groups.
- Utilization of higher strength cement increased compressive strength.
- Augmenting of aggregate/cement ratio increased the compressive strength of the mixtures.
- Statistical analysis revealed that water/cement ratio was the most effective factor on compressive strength while the cement type and content has a lower influence on compressive strength.
- We proposed a mathematical model that considers all necessary parameters.
- There is a high correlation between experimental and predicted compressive strength values derived by GEP and MLR.
- However, the model derived by GEP gave better performance than one proposed by MLR.

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