COMPARISON OF TEST METHODS ON THE COMPRESSIVE STRENGTH OF SLAG AND NATURAL POZZOLAN CEMENTS

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ABSTRACT

COMPARISON OF TEST METHODS ON THE COMPRESSIVE STRENGTH OF SLAG AND NATURAL POZZOLAN CEMENTS

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Among the two standard test methods of determining the compressive strength of cements which are described in EN 196-1 and ASTM C 109, the basic differences is in the amount of water used in preparing the mortars. According to EN 196-1 the former uses a constant water-cement ratio of 0.50 in the preparation of mortar specimens, for all types of cements whereas the latter uses a constant water-cement ratio of 0.485 and 0.460 for Portland and air-entrained Portland cements, respectively; and water-cement ratio that corresponds to a specified workability (110 ± 5% flow) for blended cements.

Presence of mineral additives in the blended cements would result in stiff mortar specimens when the same compactive effort is applied as described in EN 196-1. On the other hand, when the constant flow criterion of ASTM C 109 is applied, this would lead to higher water-cement ratios. Variability of the strength test results could be higher, in both cases either due to insufficient compaction or higher water-cement ratio, respectively. In this thesis, a third method of strength specimen preparation based on constant volumetric water-cement ratio was proposed.

The aim of this thesis is to show the variabilities that can be encountered in the determination of compressive strength of blended cements. For this purpose, ground granulated blast-furnace slag (GGBFS) and natural pozzolan-incorporated blended cements were used. 20%, 35%, 55% GGBFS and 20%, 35%, 55% natural pozzolan-incorporated blended cements are selected and 7-day and 28-day compressive strength of mortars, which are obtained by the 3 different methods, constant water/cementitious by mass (TS EN 196-1), constant flow (ASTM) and constant water/cementitious by volume methods, are determined. Then, coefficients of variation of the results obtained by the three methods are compared. The variabilities involved in the two standard methods and the proposed method was comparatively studied by statistical analyses of the experimental results obtained.

According to the results of the studies, deviations of the compressive strength results obtained from TS EN 196-1 mortars, is more than Constant Volumetric water/cementitious Mortars and ASTM C109 mortars. Therefore, it is proposed that using constant water/cementitious by mass is not suitable for blended cements.

Keywords: Ground Granulated Blast-Furnace Slag, Natural Pozzolan, Compressive Strength, Coefficient of Variation, Mortar

ÖZ

TEST YÖNTEMLERİNİN CÜRUFLÜ VE DOĞAL POZOLANLI ÇİMENTOLARIN BASINÇ DAYANIMLARI ÜZERİNDEN KARŞILAŞTIRILMASI

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Çimentoların basınç dayanımlarının belirlenmesinde kullanılan iki temel standard olan, EN 196-1 ve ASTM C 109 arasındaki temel fark harçların hazırlanmasında kullanılan su miktarıdır. EN 196-1'e göre her tip çimento için 0,50 su-çimento oranına gore su kullanılır, halbuki ASTM C 109' a göre portlant çimentosu ve hava sürüklenmiş portlant çimentosu için sırasıyla 0,485 ve 0,460 su-çimento oranında su kullanır ve katkılı çimentolar için belirli bir işlenebilirlik (110 ± 5% yayılma) değeri korunarak harç hazırlanır.

Çimentolarda mineral katkılar bulunması, test numunelerinin EN 196-1 de tarif edildiği gibi katkısız çimentolarla aynı çaba sarfedildilerek sıkıştırılmaya çalışıldığında, daha kıvamı düşük harçlara sebep olabilir. Diğer taraftan ASTM C 109'a göre sabit yayılma kriteri uygulandığında daha yüksek su-çimento oranı kullanılmasına sebep olabilir. Bu tezde, dayanım numunelerinin hazırlanması için üçüncü bir yöntem hacimsel sabit su-çimento oranı önerilmektedir.

Bu tezin amacı katkılı çimentoların basınç dayanımlarında karşılaşılabilen değişkenlikleri göstermektir. Bu amaç için öğütülmüş granule yüksek fırın cürufu ve doğal pozolan içeren katkılı çimentolar kullanılmıştır. Kütlece %20, %35, %55 yüksek fırın cürufu ve %20, %35, %55 doğal pozolan içeren katkılı çimentolar hazırlanarak kütlece sabit su/bağlayıcı oranı (TS EN 196-1), sabit yayılma değeri

(ASTM) ve hacimce sabit su/bağlayıcı oranı olarak 3 farklı yönteme göre 7 ve 28 günlük basınç dayanımları belirlenmiştir. Daha sonra, üç yöntemden elde edilen basınç dayanım sonuçlarının varyasyon katsayıları karşılaştırılmıştır. İki standart test metodunun ve önerilen metodun değişkenliği, elde edilen deney sonuçlarının istatistiksel analizleri yapılarak karşılaştırılmıştır.

Yapılan çalışmaların sonuçlarına göre, EN 196-1 yöntemiyle elde edilen harçların basınç dayanım sonuçlarındaki sapmalar, hacimce sabit su/bağlayıcı oranı ve ASTM C 109 yöntemleriyle elde edilen harçların basınç dayanım sonuçlarına göre daha fazladır. Sonuç olarak katkılı çimentolar için kütlece sabit su/bağlayıcı oranı yönteminin kullanılmasının uygun olmadığı sonucuna varılmıştır.

Anahtar Sözcükler: Öğütülmüş Granule Yüksek Fırın Cürufu, Doğal Puzolan, Çimento Basınç Dayanımı, Varyasyon Katsayısı, Harç

To My Wife

To My Daughter

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ANOVA	: Analysis of variance
ASTM	: American Society for Testing Materials
C-Flow	: Constant Flow
C-Mw	: Constant Water/Cementitious by Mass
C-Vw	: Constant Water/Cementitious by Volume
EN	: European Norm
GGBFS	: Ground Granulated Blast-Furnace Slag
METU	: Middle East Technical University
NP20	: 20% Natural Pozzolan-blended cement
NP35	: 35% Natural Pozzolan-blended cement
NP55	: 55% Natural Pozzolan-blended cement
S20	: 20% Slag-blended cement
S35	: 35% Slag-blended cement
S55	: 55% Slag-blended cement
CV	: Coefficient of Variation
TCMA	: Turkish Cement Manufacturers' Association
TS	: Turkish Standard
TSE	: Turkish Standard Institute

CHAPTER 1

INTRODUCTION

1.1. General

The construction industry is the leading sector of the Turkish economy, and cement industry is one of the most important parties of the construction sector in Turkey. As seen in Figure 1, cement production reached 63.6 Mt in 2012, according to annual cement production statistics of Turkish Cement Manufacturers' Association (TCMA). Cement production has a rising growth because of urban construction projects. In Turkey; According to CEMBUREAU Activity Report 2012; domestic cement demand is expected to increase by around 4% to 5% in 2013.

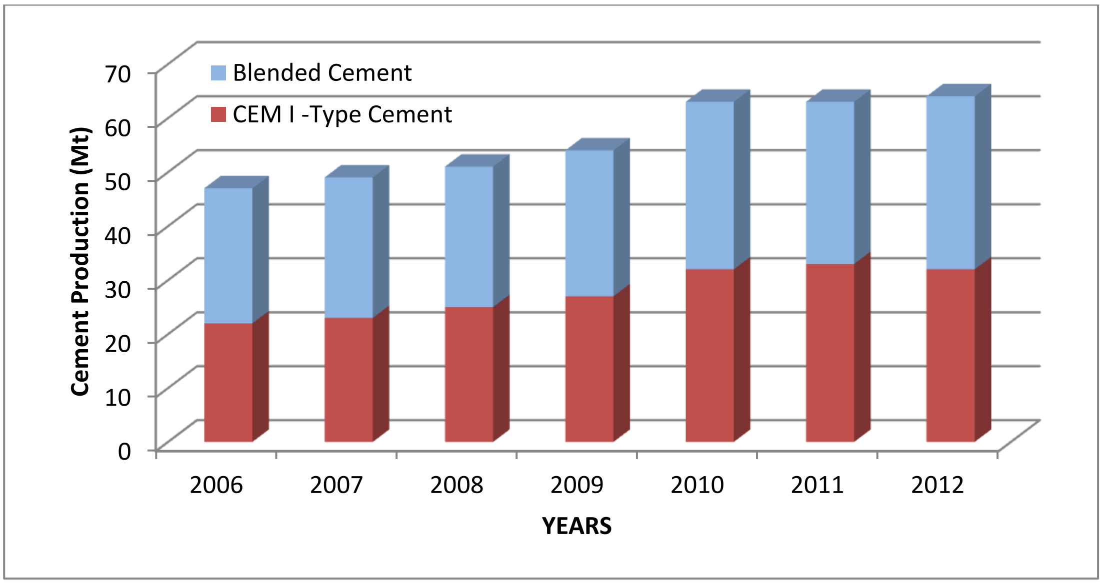


Figure 1 Annual Cement Production in Turkey [1]

Cement production is an energy-intensive process. About 60 to 130 kg of fuel oil or its equivalent and about 105 kWh of electricity are used to produce one ton of cement [2]. So, using by-products is important not only to decrease the cost, but also to produce environmental friendly products. Cement sector consumes natural resources so cement manufacturers need to achieve the environmental sustainability. Resource efficient and eco-friendly products and increasing consumer awareness are fostered in Europe to have environmental sustainability [3]. In order to integrate to the regulations, policies and environmental sustainability, cement manufacturers have made several arrangements on their processes and product ranges [4]. In order to decrease the clinker content, cement manufacturers utilize natural or by product additives. Cements that are produced using additives are called blended cements. As seen in Figure 1, almost half of the cement in Turkey is produced as blended cements for each year. Cement properties change by utilizing additives in cement production. Both, type of additives and amount of the additives affect the properties of cement. For instance; using additives such as natural pozzolan and slag, increase the specific surface area of cement particles and leads to an increase in the water requirement of cement. In Turkey, strength properties of all types of cement are determined by TS EN 196-1 which describes exactly the same procedure for all types of cement. Thus using constant water content may not provide enough water for workable blended cement mortars and it causes stiff mixes. However, ASTM C 109 describes three different methods of specimen preparation for Portland, air-entrained Portland, and blended cements. The main difference between the two standard methods lies in the amount of water used and the workability of the fresh mortars prepared.

1.2. Objective and Scope of the Thesis

The main objective of this thesis is to show the variabilities that can be encountered in the determination of compressive strength of blended (slag and natural pozzolan) cements. Six different blended cements, which includes 20%, 35%, 55% slag and 20%, 35%, 55% natural pozzolan, were selected and for each cement type three different mortars were prepared. The water content of each mortar was determined by using different amounts of water as follows;

i) Constant water/cementitious by mass (TS EN 196-1),
ii) Constant flow (ASTM),
iii) Constant water/cementitious by volume.

This thesis consists of five chapters:

In Chapter 2, role of the cement in concrete is explained briefly. Then, cement types according to Harmonized Turkish standard TS EN 197-1 are defined. Then general classification and typical examples of mineral admixtures were listed. Moreover, mineral additives used in the cement production and effects of mineral additives on the properties of cement are briefly mentioned. Finally, the quality control applications for cements are outlined and two different compressive strength test methods (ASTM C 109 and EN 196-1) are compared.

In Chapter 3, the properties of materials used in the study and the details of mixture preparation are given. Then evaluation procedure of strength test data was presented.

In Chapter 4, the compressive strength test results of cement types S20, S35, S55, NP20, NP35 and NP55 are presented. Also, results are statistically analyzed and evaluated for all methods.

In Chapter 5, the conclusions of the study resulting from the findings of the tests, observations, and the recommendations to future researchers are written.

CHAPTER 2

THEORETICAL CONSIDERATIONS

2.1. Portland Cement

Cement comprises the paste of concrete together with water, which binds the aggregates (sand and gravel or crushed stone) to form a rigid mass as the paste hardens with the help of the chemical reaction of the cement and water [5]. The quality of the paste, aggregate and the bond between the two, determine the quality of the concrete [5].Thus, strength of cement is very closely related with strength of concrete. Generally, strength is considered as the most important property. Because, it is easier to determine than many other properties and also many properties may be deduced from strength data.

Harmonized Turkish standard TS EN 197-1, defines 27 common types of cements, 7 sulfate resisting cements (SR-Cements) and low early strength cements. And it defines 9 different strength classes [6]. Except for Portland cement CEM I, all other cements are blended cements.

Natural and artificial (industrial) mineral additives have been used in the production of cement and concrete, for a long time. General classification and typical examples of mineral admixtures can be listed as follows; [7]

- Those with latest binding properties; e.g. Water-cooled (granulated) blast furnace slag
- Those with pozzolanic activity and binding properties; e.g. Calcareous fly ash
- Those with high pozzolanic activity; e.g. Silica fume, rice husk ash

- Normal pozzolans; e.g. Siliceous fly ash, natural or calcined pozzolans
- Those with low pozzolanic activity; e.g. Slow-cooled blast furnace slag various natural pozzolan, various boiler slag, plant ashes
- Inert ones; e.g. Finely ground quartz, limestone, bentonite

The cement production process requires high energy and large amounts of raw materials. European cement industry almost reached the limits of technical improvements to lower the environmental impact of the cement production. Another way to reduce environmental impacts is reducing of the clinker content in cement (blended cements). Granulated blast furnace slag (gbs), fly ashes, natural and industrial pozzolans or limestone can be used as main constituents of cement. In order to produce blended cements, less clinker and so lower emission and lower energy consumption is needed. Essentially, European cement standards allow the partial replacement of cement clinker by admixtures. Granulated slags from the production of pig iron, fly ash and uncalcined limestone have found significant use in cement production throughout the world [8].

Using the suitable mineral admixtures during the manufacture of cement provides significant economic, environmental and technical advantages. Usually, mineral additives are added after obtaining the clinker and grinded with clinker. Therefore, less raw material (natural source) and less energy is used to obtain cement that leads to less greenhouse gas emission to the atmosphere. If the additive is an industrial waste, environmental benefits will be even more [7].

As a result, using mineral additives with cement may be useful for;

- Economics and energy conservation,
- Protection of natural resources and environment, reduction of greenhouse gases,
- Reduction of the heat of hydration,
- Increasing the workability and durability of cementitious products.

2.2 Main Constituents of Cement

In order to decrease the cost and produce more environmental friendly products, natural minerals or by-products of some other industrial processes, are used in cement. In addition they are generally called as blended cements [6]. Natural pozzolan, artificial pozzolan, silica fume, granulated blast furnace slag, fly ash, burnt shale and limestone are listed as main constituents of cement in TS EN 197-1, besides clinker. According to cement type, the percentage of these materials in cements varies. Table 1 states the limits of the composition of the cements that confirming the TS EN 197-1.

Table 1 Composition of the 27 Common Cements

Main types	Notation of the 27 products (types of common cement)		Composition (percentage by mass[a])										
			Main constituents										Minor additional constituents
			Clinker	Blast-furnace slag	Silica fume	Pozzolana natural	Pozzolana natural calcined	Fly ash siliceous	Fly ash calca-reous	Burnt shale	Limestone		
			K	S	D[b]	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-pozzolana 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-burnt shale cement	CEM II/A-T	80-94	–	–	–	–	–	–	6-20	–	–	0-5
		CEM II/B-T	65-79	–	–	–	–	–	–	21-35	–	–	0-5
	Portland-limestone 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[c]	CEM II/A-M	80-88	← 12-20 →									0-5
		CEM II/B-M	65-79	← 21-35 →									0-5
CEM III	Blast furnace 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[c]	CEM IV/A	65-89	–	← 11-35 →					–	–	–	0-5
		CEM IV/B	45-64	–	← 36-55 →					–	–	–	0-5
CEM V	Composite cement[c]	CEM V/A	40-64	18-30	–	← 18-30 →			–	–	–	–	0-5
		CEM V/B	20-38	31-49	–	← 31-49 →			–	–	–	–	0-5

a The values in the table refer to the sum of the main and minor additional constituents.

b The proportion of silica fume is limited to 10 %.

c In Portland-composite cements CEM II/A-M and CEM II/B-M, in pozzolanic cements CEM IV/A and CEM IV/B and in composite cements CEM V/A and CEM V/B the main constituents other than clinker shall be declared by designation of the cement (for examples, see Clause 8).

2.2.1 Ground Granulated Blast Furnace Slag (S)

Ground granulated blast furnace slag is produced when iron ore is reduced by coke at about 1350–1550℃ in a blast furnace. Molten iron, the main product of the blast furnace, is extracted from the ore, while the other components form a liquid slag. Granulated slag is produced by quenching the liquid slag with a large amount of water to produce sand-like granulates [9]. According to TS EN 197-1 the sum of calcium oxide (CaO), magnesium oxide (MgO) and silicon dioxide (SiO_2) shall consist of at least 66% of the granulated blast furnace slag by mass. The rest of the composition is aluminum oxide (Al_2O_3) together with small amounts of other compounds. Also, (CaO + MgO)/ (SiO_2) ratio by mass shall exceed 1.0 [6].

2.2.2 Natural Pozzolan (P, Q)

Materials originated from volcanic eruption are usually called as natural pozzolans [10]. Natural pozzolans chemically reacts with the calcium hydroxide released by the hydration of Portland cement to form calcium silicate hydrate and other cementitious compounds [5]. According to TS EN 197-1, natural pozzolans are named as natural and natural calcined pozzolans which are abbreviated by P and Q respectively.

2.2.3 Effects of the GGBFS and NP on Mortar and Concrete Properties

Chemical compositions of GGBFS and NP are different from clinker so that, they influence the some properties of cement.

2.2.3.1 Water Requirement

The amount of mixing water required for a specified consistency of a mortar or concrete is called as water requirement. Newman (2003) claims that; for the same slump value, GGBFS concretes need about 3% less water when compared with Portland cement concrete. This reduction usually related with retardation in chemical reactions and smooth surface texture of slag particles [11]. In addition, specific gravity of blast furnace slag is lower than clinker, so that formen need extra water to have same workability of concrete.

Natural pozzolans increase the water demand of concrete. Using natural pozzolan in cement, increases water requirement and decreases initial strength. Because the natural pozzolans increase the specific surface area, cements containing natural pozzolans have higher water requirement, to ensure same consistency with ordinary Portland cement [12]. So, these factors are limiting the usage of natural pozzolan to 30% in blended cement production [19].

2.2.3.2 Workability

Workability is defined as the ease of the concrete mixing, handling, compacting, placing and finishing. There are several factors affecting workability such as composition and fineness of the cement, presence and amount of admixtures, proportions, and temperature conditions [5]. The lubricant effect and morphology improvement on cement mortar of natural pozzolans increase with an increase in fineness of the cementitious materials [13]. As a result, natural pozzolans improve the consistency and the workability of the concrete.

2.2.3.3 Strength

Strength of concrete is considered to be its most important property. The early strength of cements containing GGBFS and natural pozzolan is slightly lower and decrease with increasing content of these main constituent [8]. However, provided a suitable moist environment, the long-term strength of GGBFS and natural pozzolan blended cements will likely be higher [11].

It is well known that for a concrete mix that is well compacted when water/cement ratio decreases, the strength of concrete increases. However, when water/cement ratio decreases, concrete cannot be compacted well because of stiffness of mortar.

Thus at very low water/cement ratio, concrete strength decreases as shown in Figure 2, because of insufficient compaction [16,17].

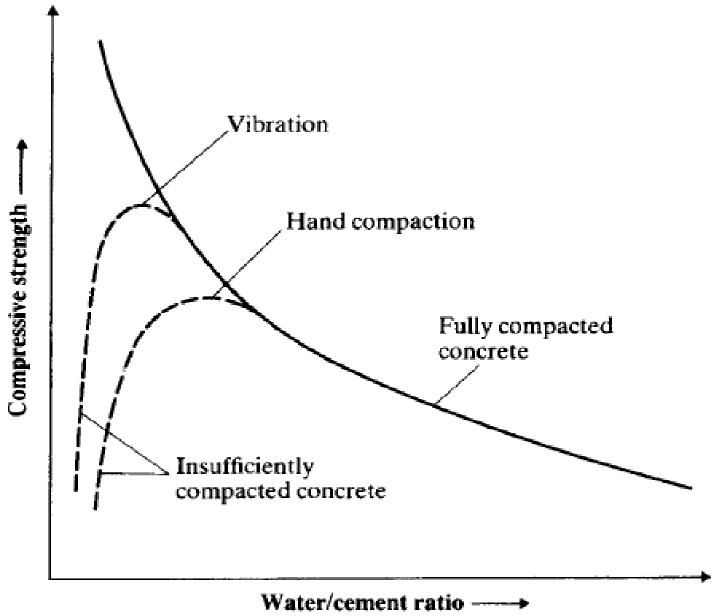


Figure 2 Relation Between Strength and Water/Cement Ratio of Concrete [16, 17]

2.3 Factors Affecting the Concrete Strength

Concrete is a composite material and there are several factors affecting the strength of concrete such as constituents and their mixing proportions, test method applied for the determination of strength etc. Some factors which affect the concrete strength are as follows:

- Quality of cement
- Quality of aggregates
- Water to cement ratio
- Chemical composition
- Admixtures
- Age of paste
- Moisture content
- Load rate

2.3.1 Materials and Their Mixing Proportions

Cement, water, aggregate and chemical admixtures comprises of concrete so that properties of each of these materials have an influence on the strength of concrete. Mainly, cement type, particle size distribution of cement and aggregates are some of the factors related to constituents. Beside the properties of the constituents, mixing proportions of these materials have an important influence on the strength of concrete. In order to produce an economical concrete having the desired properties, there is always an optimum mixing proportions for these materials. Especially, water to cement ratio is an important parameter, because excessive water may result bleeding and segregation of concrete or less amounts of water may result stiff mixes.

2.3.2 Test Method

Different standards propose different test methods and different specimen molds to determine the compressive strength of cement and concrete. For example, load rate of the test machines; ASTM C109 defines the range of the load rate as 900 to 1800 N/s and EN 196-1 defines the load rate as (2400 ± 200) N/s. Moreover in ASTM C109, 50 mm cubic mold is used for the determination of compressive strength of cement, whereas in TS EN 196-1 a 40 × 40 × 160 mm prism is used.

2.4 Quality Control Applications in Cement

Using mineral admixtures with clinker, during the manufacture of cement, causes differences in both the density and the fineness of blended cement. So that, the density and the fineness blended cements differ from ordinary Portland cements according to amount of additives, which in turn affects the workability of cement mortars.

In Turkey, strength properties of all types of cement are determined by TS EN 196-1 which describes exactly the same procedure for all types of cement. Thus using constant water content does not provide enough water for workable blended cement mortars and it causes stiff mixes. However, ASTM C 109 describes three different methods of specimen preparation for Portland, air-entrained Portland, and blended cements. Main characteristic properties of the two standards can be seen at Table 1. The main difference between the two standard methods lies in the amount of water used and the workability of the fresh mortars prepared.

Table 2 Main Characteristic Properties of ASTM C 109 & EN 196-1.

		ASTM C 109		EN 196-1
cement types	PC	Air-Ent PC	Blended cements	All Cements
cement	1	1	1	1
sand	2.75	2.75	2.75	3
water	0.485	0.46	by flow	0.5
w/c	0.485	0.46	by flow	0.5
molds	50 mm test cubes			(40x40x160)mm test prisms
tamping	2 layers & hand tamping			2 layers & tamping by device
curing conditions	saturated lime water at (23.0 ± 3.0 °C)			tap water at (20.0 ± 1.0 °C)
loading rate	(900-1800) N/s			(2400 ± 200) N/s
test result precision	0.1 MPa			0.1 MPa

As seen in Table 2, to prepare a test mortar; for each 1 part of cement, ASTM C 109 defines 2.75 parts of standard sand, and EN 196-1 defines 3 part of standard sand. Then, ASTM C 109 defines 3 different w/c ratios for 3 different types of cements, for PC w/c is set to 0.485, for Air-Ent PC w/c is set to 0.460 and for blended cements w/c ratio is determined using the flow method. And ASTM C 109 standard requires 50 mm cubic molds whereas EN 196-1 requires (40x40x160) mm prismatic molds. Tamping procedures of the two standards are almost same; both of them describe 2-layer tamping but ASTM C 109 proposes hand tamping, however EN 196-1 proposes using tamping device. ASTM C 109 specimens are cured at (23.0 ± 3.0 °C) saturated lime water but EN 196-1 specimens are cured at (20.0 ± 1.0 °C) tap water. ASTM C109 says "Apply the load rate at a relative rate of movement between the upper and lower platens corresponding to a loading on the specimen with the range of 900 to 1800 N/s." and EN 196-1 defines the loading rate as (2400 ± 200) N/s. For both type of tests 0.1 MPa precision is required for results [14, 15].

According to EN 196-1; results shall be reported to the nearest 0.1 MPa and average of all 6 results is calculated and if one of the 6 results differs much more than ± % 10 of average value, the result is discarded. Then new average value is calculated using other 5 values. After that if one of the remaining 5 results differs much more than ± % 10 of new average value, all of the result which are related with this set, are discarded and tests are repeated with another specimen set [14]. ASTM C 109 describes the report as "Average compressive strength of all specimens from the same sample shall be reported to the nearest 0.1 MPa." In determining the compressive strength, do not consider obviously faulty results. The allowable range between specimens from the same mortar batch is 8.7 % of the average for three cubes and 7.6 % for two cubes. If the range of three specimens exceeds the defined value, discard the result which differs most from the average and check the range of the remaining specimens. After discarding faulty specimens if less than two specimens remain, retest of the sample should be made [15].

Cements are controlled by Construction Products Regulation (CPR) to ensure reliable information about performances. The Construction Products Regulation (EU) No 305/2011 (CPR) lays down harmonized conditions for the marketing of construction products and repealing Council Directive 89/106/EEC. CE Mark, the notation of French phrase "Conformité Européenne", must be attached in Turkey and

Europe shows the product satisfies the requirements set by harmonized national laws and regulations [6].

CHAPTER 3

EXPERIMENTAL STUDY

3.1 General

In order to show the variabilities that can be encountered in the determination of compressive strength of blended cements 2 different additives (slag & natural pozzolan) were chosen. Then utilizing the additives in 3 different ratios (20%, 35%, and 55%) in clinker 6 different cement types, representing CEM II, CEM III and CEM IV of EN 197-1, were prepared by TCMA-R&D laboratory. It is decided to perform the compressive strength test of slag-cements at Construction Materials Laboratory of Turkish Standard Institute (TSE) and the compressive strength test of natural pozzolan-cements at TCMA-R&D laboratory. Then, for each cement type, in order to prepare mortars, 3 different water contents were calculated according to, constant water/cementitious by mass (TS EN 196-1), constant flow(ASTM), constant water/cementitious by volume methods.

3.2 Materials

The clinker which was used in this study is obtained from Oyak Bolu Cement Plant. Natural pozzolan was taken from Bolu and GBFS was supplied by Karçimsa, the slag from the Kardemir steel plant. The chemical composition of the materials which were used in this study is presented in Table 3. In this study the ingredients were separately ground. For clinker, mineral additives and gypsum the fineness were selected as 3500 (± 200) cm^2/gr, 4000 (± 200) cm^2/gr and 3000 (± 200) cm^2/gr respectively. Later the ingredients were mixed in the proportions indicated in Table 4, to compose blended cements. Amount of gypsum was selected as 4% for 20% and 35% blended cements and 3% for 55% blended cements. The cements used in mixtures were labeled as S20, S35, S55, NP20, NP35, and NP55 according to additive amounts. All of the cements and CEN Standard Sand conforming TS EN 196-1 were obtained by TCMA-R&D laboratory.

Table 3 Chemical Composition of the Materials

Chemical Composition (%)	**Clinker (C)**	**Natural Pozzolan (NP)**	**GGBFS (S)**	**Gypsum (G)**
SiO_2	20.43	62.59	41.62	2.26
Al_2O_3	5.73	15.56	13.88	0.08
Fe_2O_3	3.25	3.86	1.08	0.28
CaO	65.50	6.79	32.72	32.16
MgO	2.67	1.77	6.98	0.68
SO_3	0.42	0.05	1.57	42.68
Na_2O	0.37	3.35	0.81	0.34
K_2O	0.58	1.62	0.86	0.12
Cl-	0.0098	-	-	-
Loss on Ignition	1.02	3.49	0.00	21.54
Na_2O eq. Alkali	0.75	4.42	1.38	0.42

3.2 Mixture Preparation of Mortars

Using the 6 different blended cements and using different water/cementitious ratios, different mortars were prepared. Used methods for calculations of water/cementitious ratios are as follows:

i. Constant water/cementitious by mass (C-Mw): Mortar shall be prepared as described at TS EN 196-1, using 450 g cement, 1350 g standard sand and 225 g water.

ii. Constant flow value (C-Flow): In this method, 1350 g of standard sand and 450 g of cementitious material are used; the amount of water is determined by the flow method when applying the flow test based on the 25 fall in 15 seconds and flow value of the mortar will be equal to 110%.

iii. Constant Water/Cementitious by Volume (C-Vw): In this method, the amount of water 225 g, 1350 g of sand to be used as the amount of binder content is calculated according to the formula given in Appendix A.

Table 5 shows the calculated mix proportions of these cement mortars.

Table 4 Mix Proportion of Blended Cements

	Mix Proportions (%)			
Label	**C**	**NP**	**S**	**G**
NP20	80	20	-	4
NP35	65	35	-	4
NP55	45	55	-	3
S20	80	-	20	4
S35	65	-	35	4
S55	45	-	55	3

For each test method, three batches of cement mortar were prepared and for each batch 3 prismatic specimens were prepared. Therefore for each test method a total of 9 specimens were used. During the compressive strength testing two measurements are obtained from 1 specimen, therefore a total of 18 compressive strength results were obtained for each test method.

Table 5 Mix Proportions of Cement Mortars

Cement Type	Method	Ingredients (g) Cement	Water	Aggregate	w/c
S20	C-Mw	450	225	1350	0.50
	C-Vw	450	229	1350	0.51
	C-Flow	450	245	1350	0.54
S35	C-Mw	450	225	1350	0.50
	C-Vw	450	233	1350	0.52
	C-Flow	450	240	1350	0.53
S55	C-Mw	450	225	1350	0.50
	C-Vw	450	238	1350	0.53
	C-Flow	450	242	1350	0.54
NP20	C-Mw	450	225	1350	0.50
	C-Vw	450	239	1350	0.53
	C-Flow	450	265	1350	0.59
NP35	C-Mw	450	225	1350	0.50
	C-Vw	450	249	1350	0.55
	C-Flow	450	272	1350	0.60
NP55	C-Mw	450	225	1350	0.50
	C-Vw	450	263	1350	0.58
	C-Flow	450	273	1350	0.61

3.3 Compressive Strength Test Procedure

The compressive strength was performed using prismatic specimens of 40x40x1600 mm. The nominal dimensions of the square area subjected to compressive force in the specimens are 40 × 40 mm. The maximum applied load P on the specimen was recorded and the compressive strength Rc was calculated using the following.

$$Rc = \frac{Fc}{1600} \tag{3.1}$$

Rc : Compressive strength, MPa,

Fc : Maximum force at fracture, N,

1600 : Test area (40 mm x 40 mm), mm^2

3.4 Evaluation of Strength Test Results

3.4.1 Check for Normality

The Grubb's test and ANOVA are valid for a data set that is normally distributed. Kolmogorov-Smirnov Test was applied to check the normality and normal distribution of all test results was seen. Results are presented in Appendix B.

Moreover, in order to evaluate distribution function of strength data; all data were divided by mean of its method. Then, according to new data; distribution function of 3 methods plotted on the same graph. Thus, 3 distribution curves centered at 1 axis. Modified distribution functions are presented in Appendix C.

3.4.2 Omission of Outliers

One problem with the results occurs when there are one or more large deviations, i.e. cases whose values differ substantially from the other observations. These points are called outliers.

In this study, data were compared by two different ways; i.e. variability of test methods (according to 18 results) and within batch variability (according to 6 results). Therefore outliers of methods and outliers of molds were calculated separately.

Firstly, in order to determine the outliers of the methods, Grubb's Test was applied. One should first verify that the data can be reasonably approximated by a normal distribution before applying the Grubbs' test. In order to check the normality of test results Kolmogorov-Smirnov Test was applied. In Grubb's Test, data set is ranked from the smallest to the largest values. Then, the mean and the standard deviation are calculated. One of the following equations is used depending on the value [21].

$$T_{Max} = \frac{(X_{Largest} - X)}{\sigma} \tag{3.2}$$

$$T_{Min} = \frac{(X - X_{Smallest})}{\sigma} \tag{3.3}$$

Where

X	: Mean of the data set
$X_{Smallest}$	: Smallest number in the data set
$X_{Largest}$	: Largest number in the data set
σ	: Standard deviation of the data set

T values are calculated and compared with the critical values given in Table 6. If both the calculated T_{Min} and T_{Max} are less than $T_{Critical}$, then it is concluded that there is no outlier in the data set. However, if one of those values or both of them are greater than $T_{Critical}$, then it is concluded that the result by which a T value greater than $T_{Critical}$, is obtained. That result is marked as an outlier and must be discarded. For all methods, there are 18 results and $g_{critical}$ value corresponding to 95% confidence for two-tail is 2.5040.

Secondly, outliers of the batches were determined according to EN 196-1. All results were compared with calculated ±10% limits of their means. If there is any result showing 10% deviance from the mean of the six results, it is discarded. Then, the remaining five results are averaged [14]. The outliers are marked at the Appendix C.

Table 6 Critical Values for Grubb's Test

n	g_{Crit} α= 0.05	g_{Crit} α= 0.01	n	g_{Crit} α= 0.05	g_{Crit} α= 0.01
3	1.1531	1.1546	15	2.4090	2.7049
4	1.4625	1.4925	16	2.4433	2.7470
5	1.6714	1.7489	17	2.4748	2.7854
6	1.8221	1.9442	18	2.5040	2.8208
7	1.9381	2.0973	19	2.5312	2.8535
8	2.0317	2.2208	20	2.5566	2.8838
9	2.1096	2.3231	21	2.6629	3.0086
10	2.1761	2.4097	22	2.7451	3.1029
11	2.2339	2.4843	23	2.8675	3.2395
12	2.2850	2.5494	24	2.9570	3.3366
13	2.3305	2.6070	25	3.0269	3.4111
14	2.3717	2.6585	26	3.0839	3.4710

3.4.3 Statistical Hypothesis Testing by ANOVA

In order to statistically analyze the variabilities coming from the experimental data, Analysis of Variance (ANOVA) analysis was performed.

Analysis of variance (ANOVA) is a statistical technique for determining the existence of differences among several population means. ANOVA is not used to show that variances are different; it is used to show that means are different.

Basically, ANOVA compares two types of variances: the variance within batch and the variance between different batches. Figure 3 helps to show how ANOVA works. The dotted arrows show the per-batch variation of the individual data points around the batch mean (the variance within). The plain arrows show the variation of the batch means around the grand mean (the variance between). The assumption of ANOVA is that; if the compressive strengths of the three molds are different, then the variance within the batches must be small compared to the variance between the batches. Hence, if the variance between batches divided by the variance within batches is large, then we say that the batches are different [20].

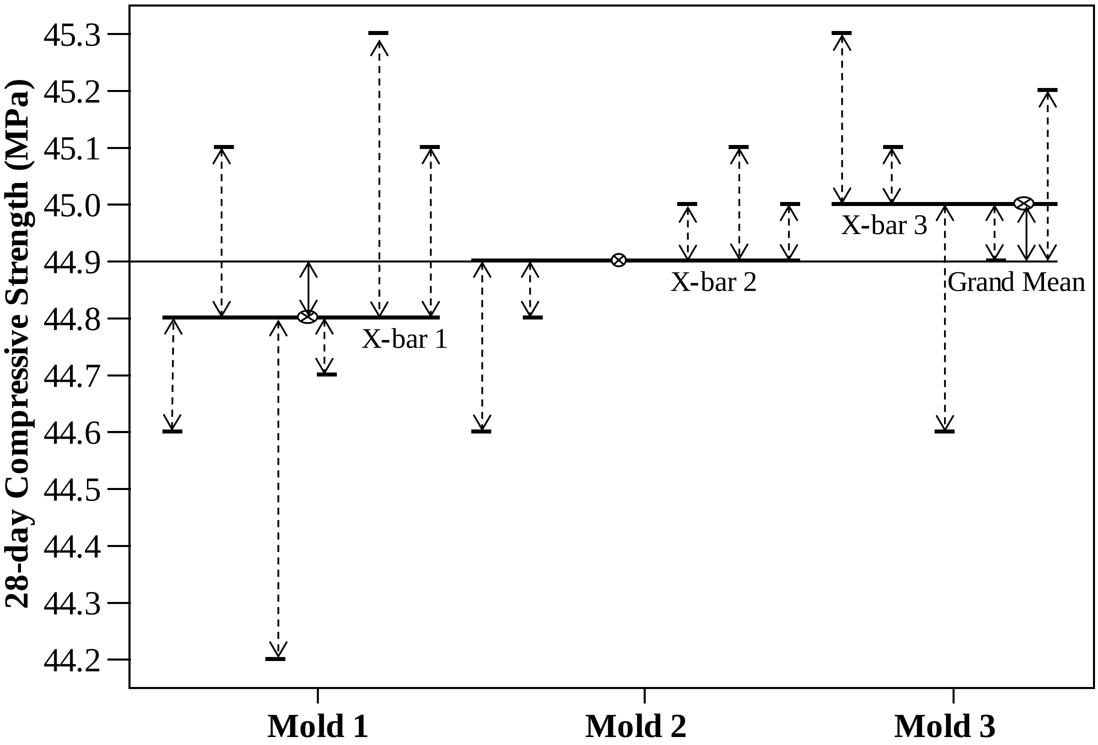


Figure 3 Comparing Variances Using ANOVA

In order to compare the compressive strength test results of all three molds, the differences between each pair; i.e. Mold 1 & Mold 2, Mold 2 & Mold 3 and Mold 1 & Mold 3 were compared using ANOVA. After analyzing all mold-pairs the closest pair which has the biggest ANOVA p-value, was determined and the third mold, out of the closest pair, was discarded. ANOVA analyses results are presented in Appendix D.

3.4.4 Comparison of the Compressive Strength Test Results

After discarding the outliers by Grubb's Test and selecting the closest mold pairs by ANOVA, mean values of all 28-day compressive strength test results, belong to two molds, were calculated and plotted against water to cement ratio, for all cements.

Then maximum and minimum values of compressive strength test results were evaluated.

3.4.5 Comparison of Variabilities Encountered by Different Test Methods

At this stage, the closest two molds results, which were decided by ANOVA, were used. For each method CV values of 28-day compressive strength test results, were calculated. Then, CV values of all cements were tabulated according to 3 methods and compared.

3.4.6 Comparison of Within Batch Variabilities of Different Test Methods

In order to compare within the batch variabilities, the closest two molds' 28-day compressive strength test results, which were decided by ANOVA, were used. Then, outliers of the batches were determined and discarded. After that, individual CV values of each mold (batch) were calculated. Then, average CV values of two molds was calculated as within batch variability for each method and displayed on a table. Finally, results were compared according to the highest and the lowest variabilities.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 General

In this study, six different types of blended cements labeled as S20, S35, S55, NP20, NP35 and NP55 were tested. For each type of cement, three different cement mortars were prepared and for each type of mortar three molds (2 of them at the same day and one of them at a different day) were cast. Then compressive strength of these mortars was tested at 7 and 28 days. 28-day results are crucial for quality control applications of cement, so all analysis was done according to 28-day results.

4.2 Slag-Blended Cements

Three different slag-blended cements, which are S20, S35 and S55, were analyzed.

4.2.1 20% Slag-Blended Cement (S20)

After confirming the normality of test results, Grubb's Test was performed for 18 results of mortar. It was seen that; there was an outlier in 28-day compressive strength results of C-Flow mortar (41.9). Then, outlier of the molds checked and (40.1) was determined as outliers at C-Vw & Mold 3. Hence, they were omitted from the test results.

After omission of outliers, ANOVA analysis was performed. Table 7 shows the ANOVA test results of S20, as can be seen; C-Mw and C-Vw methods have the biggest p-value at Mold 1 & Mold 2 and C-Flow method has the biggest p-value at

Mold 2 & Mold 3. Thus, according to the biggest p-value, the closest molds results were selected and used for analysis.

Table 7 ANOVA p-values and Selected Molds for S20

	Mold 1 & Mold 2	**Mold 2 & Mold 3**	**Mold 1 & Mold 3**
C-Mw	0.77061*	0.02269	0.07903
C-Vw	0.21320*	0.00679	0.07774
C-Flow	0.24816	0.47658*	0.30253

* denotes the selected molds for analysis.

Table E.1 shows the compressive strength test results of S20 mortar. According to Figure 4, compressive strength results of C-Mw mortar vary in between 37.0 and 41.0 MPa. The compressive strength results of C-Vw mortar vary in between 35.8 and 43.3 MPa and the compressive strength results of C-Flow mortar vary in between 35.1 and 39.3 MPa. Then, difference between upper and lower compressive strength results of C-Mw method is 4.0 MPa, C-Vw method is 7.5 MPa and C-Flow method is 4.2 MPa.

As can be seen from Figure 4, C-Vw test method gives the highest compressive strength test result as 39.7 MPa, then C-Mw mortar is 39.1 MPa and C-Flow is 37.4 MPa.

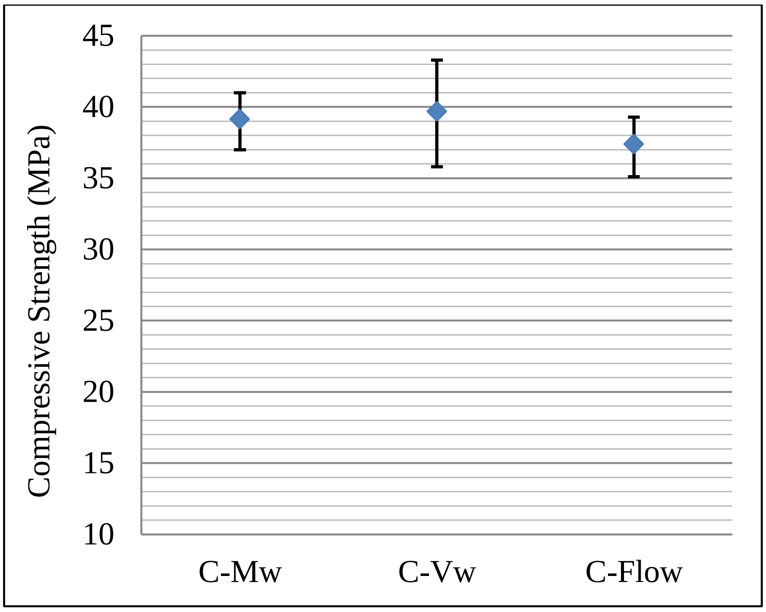


Figure 4 28-day Compressive Strength (upper, lower and mean values) of S20

4.2.2 35% Slag-Blended Cement (S35)

According to Grubb's Test; it was observed that there is no outlier belonging to any type of method. But for the outliers of the molds, there were three results that deviating more than ±10% limits of their means (43.7, 34.6 and 33.9). Then they were marked and discarded from results.

Table 8 ANOVA p-values and Selected Molds for S35

	Mold 1 & Mold 2	**Mold 2 & Mold 3**	**Mold 1 & Mold 3**
C-Mw	0.48356*	0.00039	0.00901
C-Vw	0.00252	0.61415*	0.00308
C-Flow	0.33564*	0.01341	0.00460

* denotes the selected molds for analysis.

According to Table 8, ANOVA test results of S35; C-Mw and C-Flow methods have the biggest p-value at Mold 1 & Mold 2 and C-Vw method has the biggest p-value at

Mold 2 & Mold 3. Thus, according to the biggest p-value, the closest molds results were selected and used for analysis.

Table E.2 shows the compressive strength test results of S35 mortars prepared according to C-Mw, C-Flow and C-Vw methods. As can be seen from the Figure 5, the test results of C-Mw mortar vary in between 33.9 and 43.7 MPa. The results of C-Vw mortar vary in between 39.2 and 43.1 MPa and the results of C-Flow mortar compressive strength vary in between 32.9 and 40.0 MPa. Then, difference between upper and lower compressive strength results are 9.8 MPa for C-Mw method, 3.9 MPa for C-Vw method and 7.1 MPa for C-Flow method.

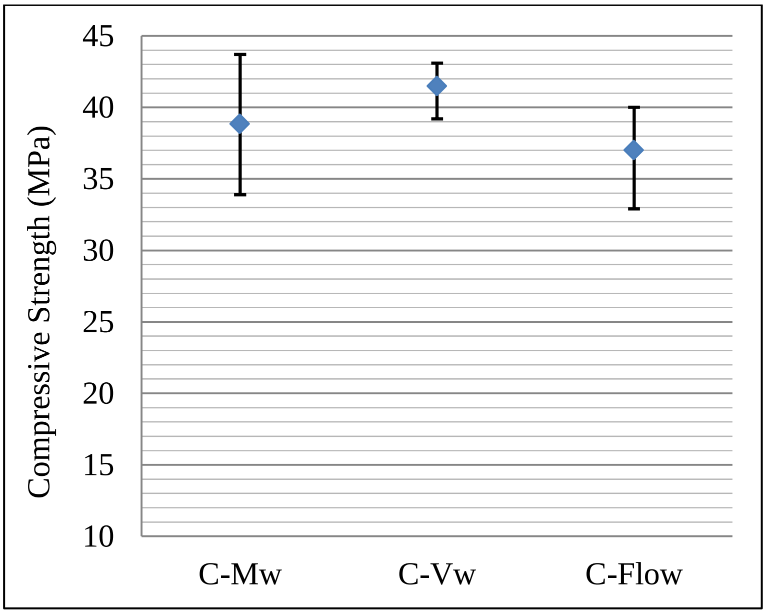


Figure 5 28-day Compressive Strength (upper, lower and mean values) of S35

For S35 cement C-Vw mortar has the biggest compressive strength test result as 41.5 MPa, then C-Mw mortar is 38.8 MPa and C-Flow is 37.0 MPa. It can be seen from Figure 5 that, C-Vw method has the smallest difference between upper and lower values and the biggest mean value according to compressive strength test results.

4.2.3 55% Slag-Blended Cement (S55)

32.6 was an outlier for method and mold analyses of 28-day compressive strength results of C-Vw mortar. Hence, it was omitted from test results.

Table 9 ANOVA p-values and Selected Molds for S55

	Mold 1 & Mold 2	Mold 2 & Mold 3	Mold 1 & Mold 3
C-Mw	0.00491	0.02324	0.61210*
C-Vw	0.03010	0.04640	0.60487*
C-Flow	0.00280	0.06287	0.06565*

* denotes the selected molds for analysis.

As can be seen at Table 9, S55 have the biggest p-value at Mold 1 & Mold 3 for all three methods. Hence, according to the biggest p-value, test results of Mold 1 & Mold 3 pairs were selected and used for analysis.

The compressive strength results of S55 mortars prepared according to C-Mw, C-Vw and C-Flow methods written on Table E.3. According to Figure 6, compressive strength test results of C-Mw mortar vary in between 32.4 and 35.5 MPa, results of C-Vw mortar vary in between 38.0 and 40.6 MPa and the results of C-Flow mortar compressive strength vary in between 30.3 and 34.9 MPa. Then, difference between upper and lower compressive strength result for C-Vw is 2.6 MPa, for C-Mw is 3.1 MPa and for C-Flow is 4.6 MPa.

C-Vw mortar has the highest compressive strength test result as 39.3 MPa, then C-Mw mortar is 34.0 MPa and C-Flow is 32.4 MPa as seen in Figure 6. It is observed that, C-Vw method also has the smallest difference between upper and lower 28-day compressive strength results.

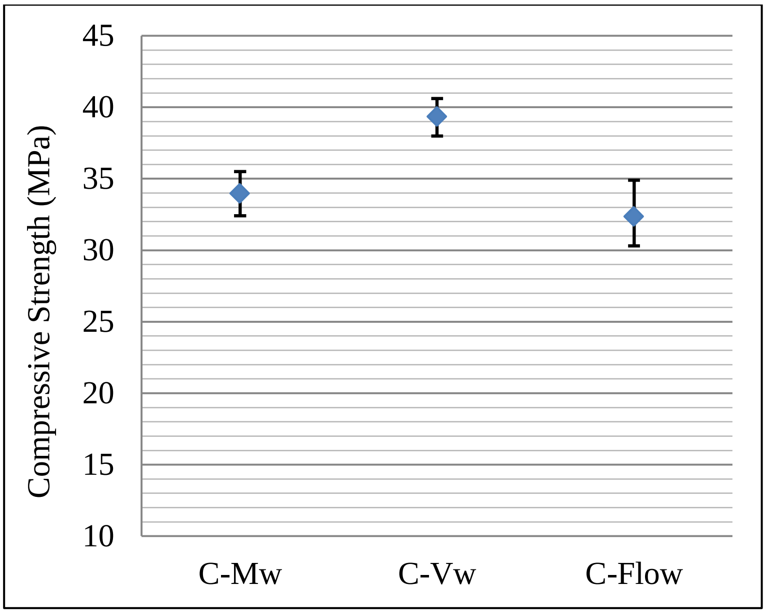


Figure 6 28-day Compressive Strength (upper, lower and mean values) of S55

4.2.4 Comparison of the Compressive Strength Test Results

After ANOVA analyses, selecting the closest mold pair, comparison of the compressive strength test results was performed by using 2 molds results. In the Figure 7, the compressive strength test results of specimens are plotted against water to cement ratio. Abrams' law states that for a mixture of workable consistency the strength of concrete is specified by the ratio of water to cement [17]. Figure 2 illustrates the effect of partial compaction.

As can be seen from Figure 7, as water content decreases compressive strength increases until the point, which is calculated according to C-Vw method, then compressive strength decreases. In spite of a reduction in the water content, a reduction in the compressive strength shows that C-Mw mortars are not compacted well. C-Mw method does not supply enough water for slag blended cements to have a good consistency for full compaction. Although C-Vw mortars include more water than C-Mw mortars, slag-blended cements have the highest strength values at C-Vw mortars. And as expected, all C-Flow mortars have the smallest compressive strength value because of increased w/c value. This behavior was schematically shown in Figure 2.

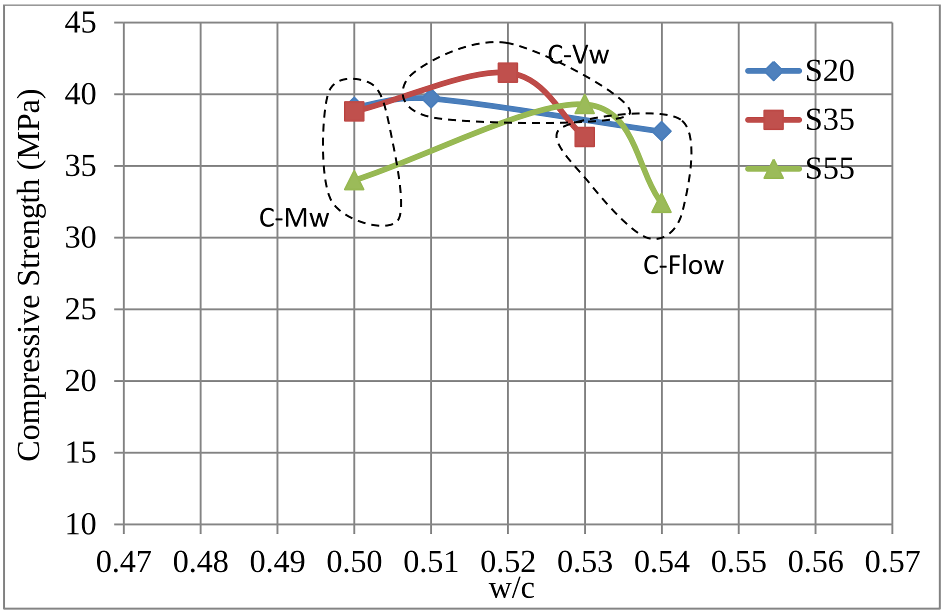
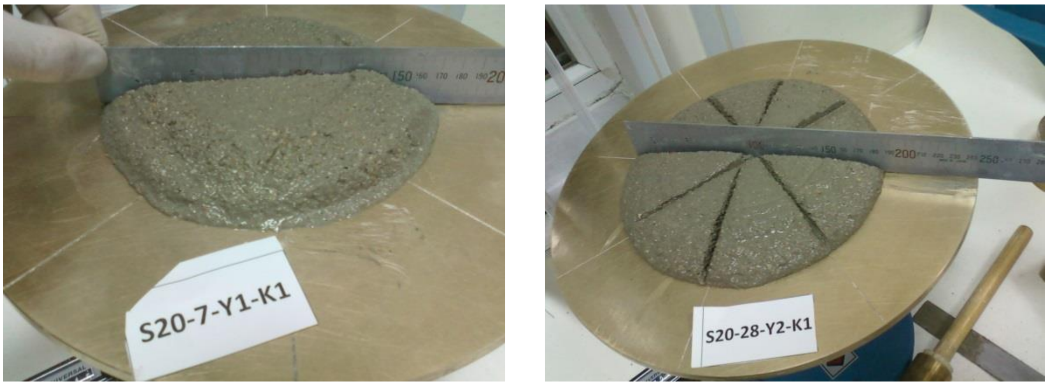


Figure 7 Compressive Strength Test Results of Slag Cements

By evaluating the Figure 8, which shows two different S20 cement mortars, some segregation and bleeding of C-Mw mortar is observed and C-Vw mortar is more flowable and workable than C-Mw mortar. It is concluded that, S20 cement with limited water can not have a good consistency at limited time of mixing.



a) C-Mw mortar (168 mm)

b)C-Vw mortar (187 mm)

Figure 8 Flow of S20 Mortars

4.2.5 Comparison of Variabilities Encountered by Different Test Methods

According to Table 10, for S20 the lowest variability was observed for C-Mw method as 3.1 %. Then for S35 the lowest variability was observed for C-Vw method as 2.8 %. Finally for S55 the lowest variability was observed for C-Vw method as 1.9 %.

Moreover, according to the ANOVA test results that shown in Table 7, Table 8 and Table 9, test results of the Mold-3s, which were not prepared at the same day as Mold-1s and Mold-2s, are not practically different from the other molds' result. In other words, casting time of the molds does not have a significant effect on the variability of compressive strength test results.

It is concluded that, for S35 and S55 blended cements, C-Vw method has the lowest variability for 28-day compressive strength test results.

Table 10 CV of 28-Day Compressive Strength Test Results

Cement Type	Methods		
	C-Mw	**C-Vw**	**C-Flow**
S20	3.1 %	5.7 %	3.2 %
S35	7.3 %	2.8 %	5.4 %
S55	3.5 %	1.9 %	4.0 %

4.2.6 Comparison of Within Batch Variabilities of Different Test Methods

According to Table 11; S20 has the lowest within the batch CV value as 2.5 % at C-Flow method. Then, S35 has the lowest within the batch CV value as 2.9 % at C-Vw method. Finally, S55 has the lowest within the batch CV value as 1.9 % at C-Vw method.

It can be concluded from Table 11 that, C-Vw method has also the lowest within batch variability for 28-day compressive strength test results of S35 and S55 blended cements.

Table 11 Within Batch CV of 28-Day Compressive Strength Test Results

Cement Type	**Methods**		
	C-Mw	**C-Vw**	**C-Flow**
S20	3.2 %	5.5 %	2.5 %
S35	4.3 %	2.9 %	5.4 %
S55	3.5 %	1.9 %	3.5 %

4.3 Natural Pozzolan-Blended Cements

Blended cements with different ratios of natural pozzolan (NP20, NP35 and NP55), were analyzed.

4.3.1 20% Natural Pozzolan-Blended Cement (NP20)

Determination of outliers of the methods is performed. It is observed that there is an outlier (34.7) belonging to C-Flow method and it is omitted. Then, outliers of the molds performed and any outlier was not determined.

Table 12 ANOVA p-values and Selected Molds for NP20

	Mold 1 & Mold 2	**Mold 2 & Mold 3**	**Mold 1 & Mold 3**
C-Mw	0.21594	0.36739	0.75936*
C-Vw	0.00472	0.00472	0.03338*
C-Flow	0.70040	0.68909	0.88894*

* denotes the selected molds for analysis.

The test result of the ANOVA for NP20 can be seen on Table 12. According to Table 12, all three methods have the biggest p-value at Mold 1 & Mold 3. Thus, all Mold 2s eliminated from analyses.

The compressive strength test results of NP20 mortars prepared according to C-Mw, C-Flow and C-Vw methods shown in Table E.4. After ANOVA analyses only results from Mold 1 and Mold 3, were used in comparison for all methods. According to Figure 13, the results of C-Mw mortar vary in between 39.7 and 43.3 MPa, the results of C-Vw mortar vary in between 37.8 and 40.1 MPa and the results of C-Flow mortar vary in between 32.6 and 33.8 MPa.

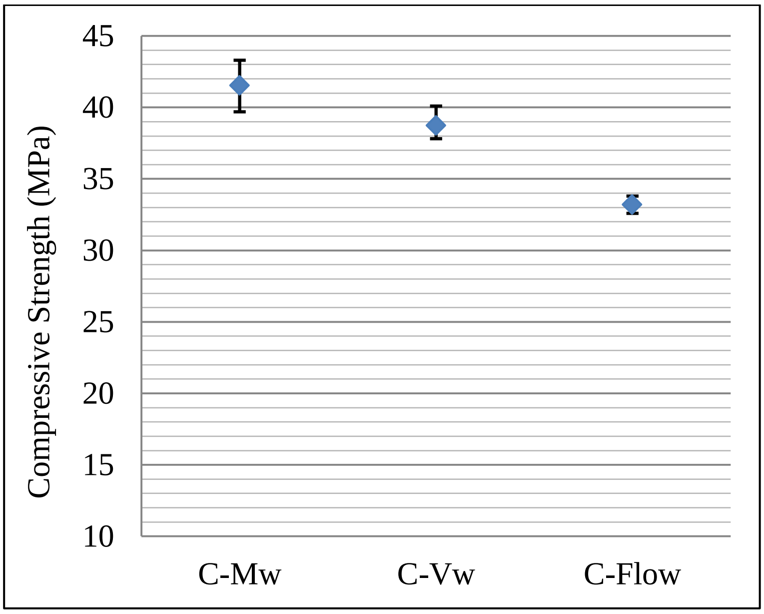


Figure 9 28-day Compressive Strength (upper, lower and mean values) of NP20

The compressive strength test result of C-Mw mortar is 41.5 MPa, the result of C-Vw mortar is 38.7 MPa and the result of C-Flow mortar is 33.2 as seen in Figure 9. According to Figure 9; C-Mw method has the highest difference between upper and lower values according to 28-day compressive strength test results.

It is obvious that, when the water content of the NP20 mortar increases, mean value of the 28-day compressive strength test results decreases.

4.3.2 35% Natural Pozzolan-Blended Cement (NP35)

When the test results were compared with the critical T value, it is observed that there is an outlier (31.3) for C-Vw method and there is an outlier (26.8) for C-Flow method. Then, when the test results were compared with calculated ±10% limits of their means, it is observed that there is no outlier for all molds.

Table 13 ANOVA p-values and Selected Molds for NP35

	Mold 1 & Mold 2	**Mold 2 & Mold 3**	**Mold 1 & Mold 3**
C-Mw	0.72754*	0.48362	0.61621
C-Vw	0.14211*	0.01101	0.06186
C-Flow	0.16173	0.14721	0.34131*

* denotes the selected molds for analysis.

According to Table 13, ANOVA test results of NP35, C-Mw and C-Vw methods have the biggest p-value at Mold 1 & Mold 2 and C-Flow method has the biggest p-value at Mold 1 & Mold 3. Thus, the closest molds results were selected and used for analyses.

The compressive strength test results of NP35 mortars prepared according to C-Mw, C-Flow and C-Vw methods can be seen at Table E.5 (appendix E). As can be seen at Figure 10, C-Mw mortar has the results in between 33.1 and 36.1 MPa, C-Vw mortar has the results between 28.8 and 29.9 MPa and C-Flow mortar has the results between 24.5 and 26.8 MPa. Then, C-Vw mortar has the lowest difference between upper and lower values of 28-day compressive strength of NP35 mortar.

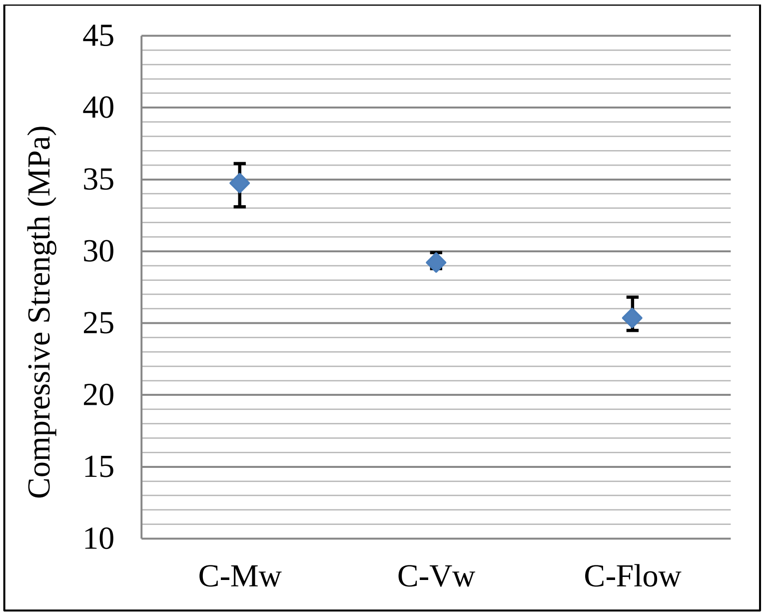


Figure 10 28-day Compressive Strength (upper, lower and mean values) of NP35

4.3.3 55% Natural Pozzolan-Blended Cement (NP55)

Determination of outliers of the methods and molds were performed. It was observed that there was an outlier (15.9) belonging to C-Flow method according to both method and mold analyses and it was omitted from results.

According to Table 14, NP55 has the biggest p-value at Mold 1 & Mold 2 for all three methods. Hence, according to the biggest p-value, test results of Mold 1 & Mold 2 pairs were selected and used for analyses.

Table E.6 (appendix E) shows the compressive strength test results of NP55 mortars. After ANOVA analysis, the closest molds were used in comparison. According to Figure 11, the results of C-Mw method vary in between 20.4 and 21.6 MPa, the results of C-Vw method vary in between 15.8 and 16.5 MPa and the results of C-Flow mortar vary in between 14.2 and 15.3 MPa. When the difference between the upper and the lower values of the compressive strength results are examined, it is observed that; C-Vw method has the lowest value as 0.7 MPa.

Table 14 ANOVA p-values and Selected Molds for NP55

	Mold 1 & Mold 2	Mold 2 & Mold 3	Mold 1 & Mold 3
C-Mw	0.94321*	0.12426	0.11139
C-Vw	0.87131*	0.00313	0.01111
C-Flow	0.72172*	0.19639	0.20190

* denotes the selected molds for analysis.

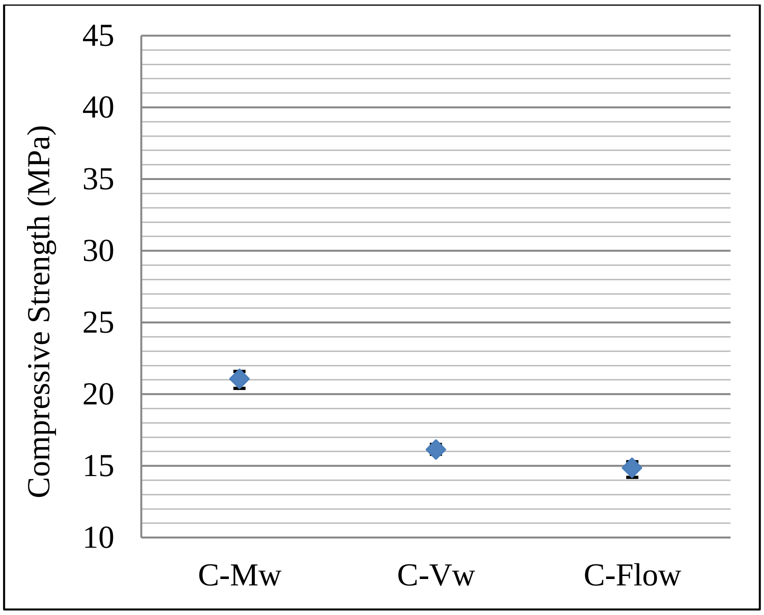


Figure 11 28-day Compressive Strength (upper, lower and mean values) of NP55

Moreover, Figure 11 shows that C-Mw method has the highest compressive strength test result as 21.1 MPa and C-Flow method has the lowest compressive strength test result as 14.9 MPa.

4.3.4 Comparison of the Compressive Strength Test Results

According to 2 closest-mold results, Figure 12 shows the 28-day compressive strength test results of specimens against water to cement ratio.

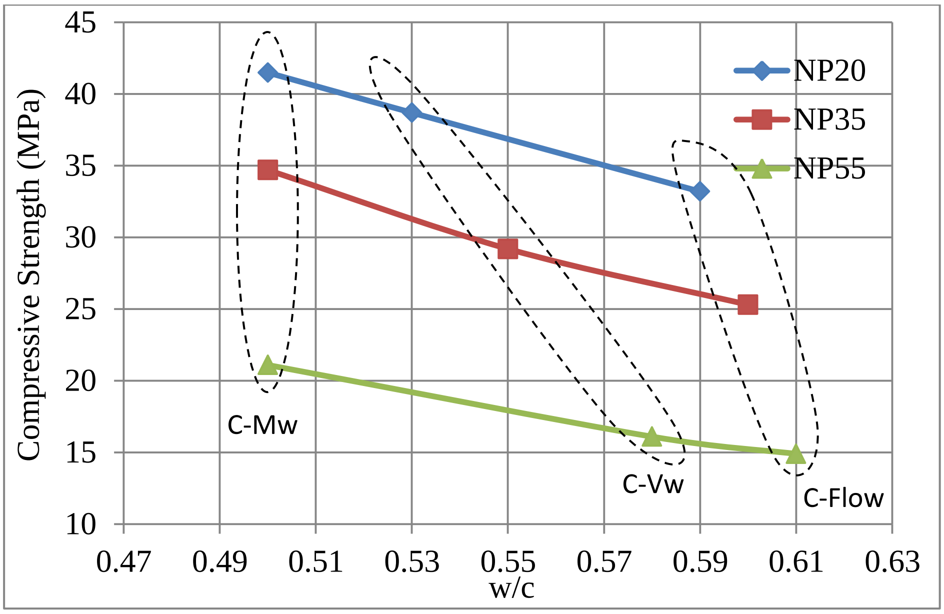


Figure 12 Compressive Strength Test Results of Natural Pozzolan Cements

As seen in Figure 12, as water content increases the compressive strength of all cements decreases. For natural pozzolan cements, C-Vw and C-Flow methods proposes more water than C-Mw method, hence C-Mw method has the highest compressive strength test results.

4.3.5 Comparison of Variabilities Encountered by Different Test Methods

It is observed from Table 15 that, for NP20 C-Mw method has the biggest CV value, for NP35 C-Vw method has the smallest CV values for NP35 and NP55.

Table 15 CV of 28-Day Compressive Strength Test Results

Cement Type	Methods		
	C-Mw	**C-Vw**	**C-Flow**
NP20	2.5 %	2.0 %	1.2 %
NP35	2.9 %	1.1 %	2.4 %
NP55	1.8 %	1.0 %	2.0 %

It is observed from Table 15 that, C-Flow method has the smallest CV value for NP20 and C-Vw method has the smallest CV values for NP35 and NP55.

In addition, Table 12, Table 13 and Table 14, ANOVA test results show that results of the Mold-3s, which were not prepared at the same day as Mold-1s and Mold-2s, are not practically different from the other molds' result. It is concluded that, casting time of the molds does not have a significant effect on the variability of compressive strength test results.

4.3.6 Comparison of Within Batch Variabilities of Different Test Methods

Table 16 Within Batch CV of 28-Day Compressive Strength Test Results

Cement Type	Methods		
	C-Mw	**C-Vw**	**C-Flow**
NP20	2.6 %	1.6 %	1.8 %
NP35	2.9 %	1.1 %	2.1 %
NP55	1.9 %	1.0 %	2.0 %

According to Table 16, NP20 has the highest within batch variability as 2.6 % at C-Mw method. Then NP35 has the highest within batch variability as 2.9 % at C-Mw method. Finally, NP55 has the highest within batch variability as 2.0 % at C-Flow method.

It is obvious that, C-Vw method has the lowest within batch variability for 28-day compressive strength test results of all natural pozzolan blended cements.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 General

Three compressive strength test methods, named as Constant Water/Cementitious by Mass, Constant Water/Cementitious by Volume, and Constant Flow were compared. Blended cements, that have different amounts of slag and natural pozzolan, were chosen. Then, slag-blended cements were tested at TSE Construction Materials Laboratory and natural pozzolan-blended cements were tested at TCMA R & D Laboratory. The results obtained from mortar tests were examined. According to the test results, the following conclusions can be drawn:

1) According to evaluation and statistical analysis of slag-blended cements; as water content decreases compressive strength increases until a point, then compressive strength decreases. In spite of a reduction in the water content, a reduction in the compressive strength shows that C-Mw method does not supply enough water for slag-blended cements to have a good consistency for full compaction. On the other hand, for natural pozzolan-blended cements such a compaction related compressive strength reduction problem was not observed.

2) Average variability of all test methods is around 4% for slag-blended cements, whereas less than 2% for natural pozzolan-blended cements. This was attributed to the differences in the experience of two labs.

3) As a result of whole experimental investigation, the average variabilities observed for C-Vw method on slag-blended cements was around 3.5%, whereas for C-Mw method it was 4.6%. On the other hand for natural pozzolan-blended cements the C-Mw method yielded an average variability of 2.4% compared to 1.4% for the C-Vw method. Therefore C-Vw method was proven to be a good alternative for determining the compressive strength of slag and natural pozzolan-blended cements.

4) For both blended cement types the C-Mw method yielded the highest variability when compared to the other two alternative methods. Therefore, C-Mw method is not the best test method for blended cements, defined in TS EN 197-1. Thus, in order to have more uniform test results, it is necessary to modify TS EN 196-1.

5) The compressive strength test results of the molds that were cast in a different day do not show significant differences from the ones that were cast on the same day. Therefore, timing of the casting of the molds is not a dominant factor, causing the variabilities for the compressive strength test results of slag and natural pozzolan-blended cements.

5.2 Recommendations for Further Studies

Considering the results of this study, following recommendations will be made for further studies.

1) In performed tests only one kind of slag and natural pozzolan were used. Thus, it is recommended to perform these tests by using other mineral additives.

2) In this study, only a limited number of specimens was tested. Therefore, it is suggested to increase the number of specimens.

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APPENDIX A

CONSTANT WATER/CEMENTITIOUS BY VOLUME METHOD

Volume Equivalence Formula

$$Fw = \frac{p}{(p+c)} \tag{A.1}$$

$$Fv = \frac{1}{1 + \frac{Gp}{Gc}(\frac{1}{Fw} - 1)} \tag{A.2}$$

$$\frac{w}{(c+p)} = \frac{Gc\frac{w}{c}}{Gc\,(1 - Fv) + Gp\,Fv} \tag{A.3}$$

w: Water content (by mass)

c: Cement content (by mass)

p: Pozzolan content (by mass)

G_p: Specific gravity of pozzolan

G_c: Specific gravity of cement

F_w: Pozzolan/total binder (by mass)

F_v: Pozzolan/total binder (by volume)

Table A.1 Specific Gravity of Ingredients

Clinker+Gypsum	Natural Pozzolan	Slag
3.19	2.43	2.89

Table A.2 Water Content for C-Vw Method

	% of Ingredients						
Cement Type	**Clinker + Gypsum**	**Natural Pozzolan**	**Slag**	**Fw**	**Fv**	**w/(c+p)**	**water (g)**
C	105	0	0				
NP20	84.0	20	0	0.19	0.24	0.53	**239**
NP35	68.3	35	0	0.34	0.40	0.55	**249**
NP55	47.3	55	0	0.54	0.60	0.58	**263**
S20	84.0	0	20	0.19	0.21	0.51	**229**
S35	68.3	0	35	0.34	0.36	0.52	**233**
S55	47.3	0	55	0.54	0.56	0.53	**238**

APPENDIX B

KOLMOGOROV-SMIRNOV TEST RESULTS

Table B.1 Kolmogorov-Smirnov Test Result of S20

a) C-Mw 28-Day Results

N		18
Normal Parameters[a]	Mean	39.661
	Std. Deviation	1.3656
Most Extreme Differences	Absolute	0.093
	Positive	0.069
	Negative	-0.093
Kolmogorov-Smirnov Z		0.396
Asymp. Sig. (2-tailed)		0.998

a. Test distribution is Normal.

b) C-Vw 28-Day Results

N		18
Normal Parameters[a]	Mean	38.494
	Std. Deviation	2.8383
Most Extreme Differences	Absolute	0.16
	Positive	0.103
	Negative	-0.16
Kolmogorov-Smirnov Z		0.678
Asymp. Sig. (2-tailed)		0.748

a. Test distribution is Normal.

c) C-Flow 28-Day Results

N		18
Normal Parameters[a]	Mean	37.45
	Std. Deviation	1.6027
Most Extreme Differences	Absolute	0.176
	Positive	0.176
	Negative	-0.124
Kolmogorov-Smirnov Z		0.746
Asymp. Sig. (2-tailed)		0.634

a. Test distribution is Normal.

Table B.2 Kolmogorov-Smirnov Test Result of S35

a) C-Mw 28-Day Results

N		18
Normal Parameters[a]	Mean	40.589
	Std. Deviation	3.4809
Most Extreme Differences	Absolute	0.112
	Positive	0.079
	Negative	-0.112
Kolmogorov-Smirnov Z		0.477
Asymp. Sig. (2-tailed)		0.977

a. Test distribution is Normal.

b) C-Vw 28-Day Results

N		18
Normal Parameters[a]	Mean	42.422
	Std. Deviation	1.7705
Most Extreme Differences	Absolute	0.122
	Positive	0.122
	Negative	-0.083
Kolmogorov-Smirnov Z		0.519
Asymp. Sig. (2-tailed)		0.95

a. Test distribution is Normal.

c) C-Flow 28-Day Results

N		18
Normal Parameters[a]	Mean	38.094
	Std. Deviation	2.3533
Most Extreme Differences	Absolute	0.124
	Positive	0.08
	Negative	-0.124
Kolmogorov-Smirnov Z		0.527
Asymp. Sig. (2-tailed)		0.944

a. Test distribution is Normal.

Table B.3 Kolmogorov-Smirnov Test Result of S55

a) C-Mw 28-Day Results

N		18
Normal Parameters[a]	Mean	33.194
	Std. Deviation	164548
Most Extreme Differences	Absolute	0.098
	Positive	0.095
	Negative	-0.098
Kolmogorov-Smirnov Z		0.415
Asymp. Sig. (2-tailed)		0.995

a. Test distribution is Normal.

b) C-Vw 28-Day Results

N		18
Normal Parameters[a]	Mean	38.478
	Std. Deviation	1.9365
Most Extreme Differences	Absolute	0.236
	Positive	0.137
	Negative	-0.236
Kolmogorov-Smirnov Z		1.001
Asymp. Sig. (2-tailed)		0.269

a. Test distribution is Normal.

c) C-Flow 28-Day Results

N		18
Normal Parameters[a]	Mean	32.983
	Std. Deviation	1.4786
Most Extreme Differences	Absolute	0.155
	Positive	0.101
	Negative	-0.155
Kolmogorov-Smirnov Z		0.659
Asymp. Sig. (2-tailed)		0.778

a. Test distribution is Normal.

Table B.4 Kolmogorov-Smirnov Test Result of NP20

a) C-Mw 28-Day Results

N		18
Normal Parameters[a]	Mean	41.783
	Std. Deviation	1.131
Most Extreme Differences	Absolute	0.117
	Positive	0.11
	Negative	-0.117
Kolmogorov-Smirnov Z		0.497
Asymp. Sig. (2-tailed)		0.966

a. Test distribution is Normal.

b) C-Vw 28-Day Results

N		18
Normal Parameters[a]	Mean	38.894
	Std. Deviation	0.6915
Most Extreme Differences	Absolute	0.1
	Positive	0.083
	Negative	-0.1
Kolmogorov-Smirnov Z		0.425
Asymp. Sig. (2-tailed)		0.994

a. Test distribution is Normal.

c) C-Flow 28-Day Results

N		18
Normal Parameters[a]	Mean	33.289
	Std. Deviation	0.4922
Most Extreme Differences	Absolute	0.133
	Positive	0.133
	Negative	-0.095
Kolmogorov-Smirnov Z		0.564
Asymp. Sig. (2-tailed)		0.908

a. Test distribution is Normal.

Table B.5 Kolmogorov-Smirnov Test Result of NP35

a) C-Mw 28-Day Results

N		18
Normal Parameters[a]	Mean	34.644
	Std. Deviation	0.8535
Most Extreme Differences	Absolute	0.15
	Positive	0.15
	Negative	-0.091
Kolmogorov-Smirnov Z		0.636
Asymp. Sig. (2-tailed)		0.813

a. Test distribution is Normal.

b) C-Vw 28-Day Results

N		18
Normal Parameters[a]	Mean	29.467
	Std. Deviation	0.5831
Most Extreme Differences	Absolute	0.176
	Positive	0.176
	Negative	-0.126
Kolmogorov-Smirnov Z		0.748
Asymp. Sig. (2-tailed)		0.631

a. Test distribution is Normal.

c) C-Flow 28-Day Results

N		18
Normal Parameters[a]	Mean	25.222
	Std. Deviation	0.5242
Most Extreme Differences	Absolute	0.201
	Positive	0.201
	Negative	-0.155
Kolmogorov-Smirnov Z		0.851
Asymp. Sig. (2-tailed)		0.464

a. Test distribution is Normal.

Table B.6 Kolmogorov-Smirnov Test Result of NP55

a) C-Mw 28-Day Results

N		18
Normal Parameters[a]	Mean	21.183
	Std. Deviation	0.3666
Most Extreme Differences	Absolute	0.132
	Positive	0.093
	Negative	-0.132
Kolmogorov-Smirnov Z		0.561
Asymp. Sig. (2-tailed)		0.911

a. Test distribution is Normal.

b) C-Vw 28-Day Results

N		18
Normal Parameters[a]	Mean	16.267
	Std. Deviation	0.2808
Most Extreme Differences	Absolute	0.261
	Positive	0.261
	Negative	-0.116
Kolmogorov-Smirnov Z		1.105
Asymp. Sig. (2-tailed)		0.174

a. Test distribution is Normal.

c) C-Flow 28-Day Results

N		18
Normal Parameters[a]	Mean	14.967
	Std. Deviation	0.3694
Most Extreme Differences	Absolute	0.137
	Positive	0.137
	Negative	-0.105
Kolmogorov-Smirnov Z		0.581
Asymp. Sig. (2-tailed)		0.889

a. Test distribution is Normal.

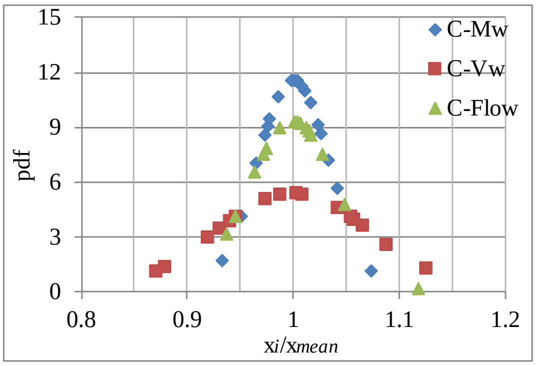
APPENDIX C

MODIFIED DISTRIBUTION FUNCTIONS OF CEMENTS AT 28 DAY

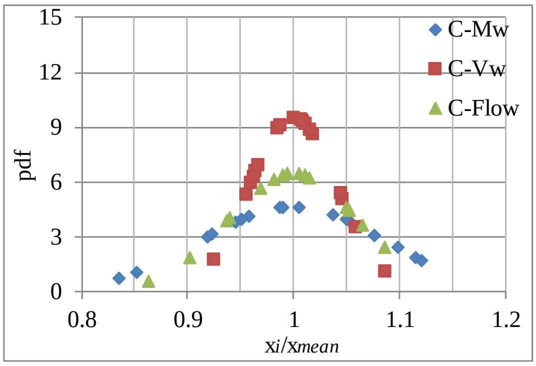
pdf : Probability distribution function

x*i* : Individual compressive strength test results (MPa)

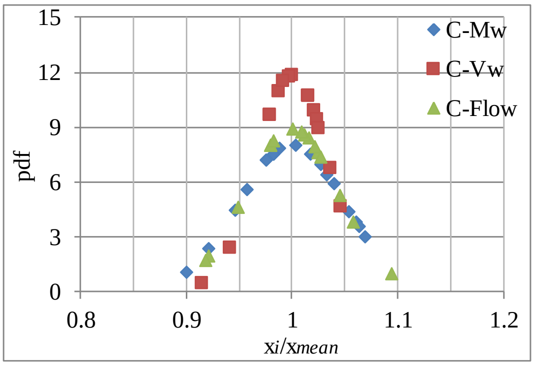
x*mean* : Average compressive strength test result for each method (MPa)



a) S20

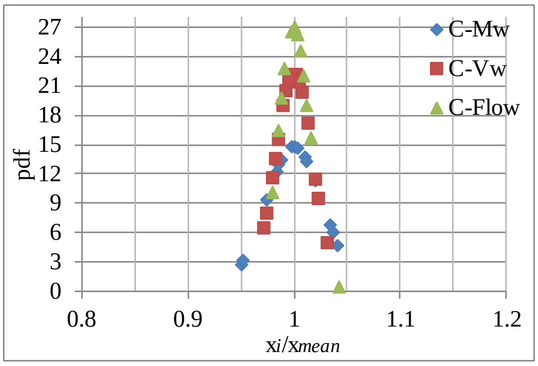


b) S35

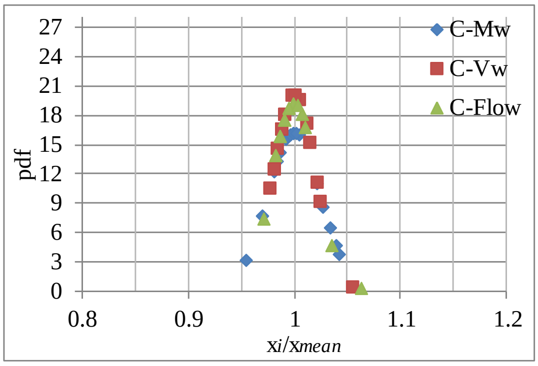


c) S55

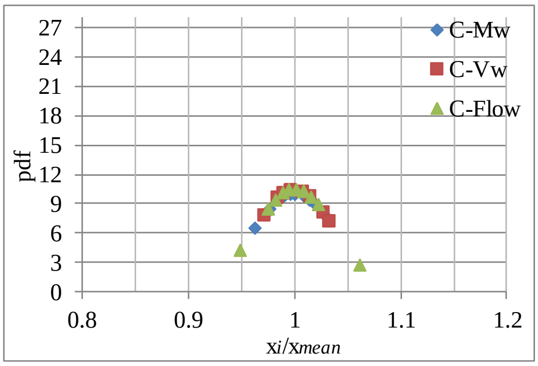
Figure C.1 Modified Distribution Functions of Slag Cements



a) NP20



b) NP35



c) NP55

Figure C.2 Modified Distribution Functions of Natural Pozzolan Cements

APPENDIX D

ANOVA ANALYSES RESULTS

Table D.1 ANOVA Analyses of S20

a) C-Mw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.141	1	0.141	0.08977	0.77061	4.96460
Within Groups	15.688	10	1.569			
Total	15.829	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	8.333	1	8.333	7.23798	0.02269	4.96460
Within Groups	11.513	10	1.151			
Total	19.847	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	6.307	1	6.307	3.82389	0.07903	4.96460
Within Groups	16.495	10	1.650			
Total	22.803	11				

b) C-Vw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	8.333	1	8.333	1.76766	0.21320	4.96460
Within Groups	47.143	10	4.714			
Total	55.477	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	58.080	1	58.080	11.54748	0.00679	4.96460
Within Groups	50.297	10	5.030			
Total	108.377	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	22.413	1	22.413	3.86281	0.07774	4.96460
Within Groups	58.023	10	5.802			
Total	80.437	11				

c) C-Flow Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	5.467	1	5.467	1.50392	0.24816	4.96460
Within Groups	36.355	10	3.636			
Total	41.823	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	1.688	1	1.688	0.54691	0.47658	4.96460
Within Groups	30.855	10	3.086			
Total	32.543	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	1.080	1	1.080	1.18162	0.30253	4.96460
Within Groups	9.140	10	0.914			
Total	10.220	11				

Table D.2 ANOVA Analyses of S35

a) C-Mw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	4.441	1	4.441	0.52937	0.48356	4.96460
Within Groups	83.888	10	8.389			
Total	88.329	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	102.668	1	102.668	27.24601	0.00039	4.96460
Within Groups	37.682	10	3.768			
Total	140.349	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	64.403	1	64.403	10.43758	0.00901	4.96460
Within Groups	61.703	10	6.170			
Total	126.107	11				

b) C-Vw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	26.108	1	26.108	15.99561	0.00252	4.96460
Within Groups	16.322	10	1.632			
Total	42.429	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.403	1	0.403	0.27075	0.61415	4.96460
Within Groups	14.897	10	1.490			
Total	15.300	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	20.021	1	20.021	15.02878	0.00308	4.96460
Within Groups	13.322	10	1.332			
Total	33.343	11				

c) C-Flow Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	4.083	1	4.083	1.02305	0.33564	4.96460
Within Groups	39.913	10	3.991			
Total	43.997	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	21.068	1	21.068	8.98209	0.01341	4.96460
Within Groups	23.455	10	2.346			
Total	44.523	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	43.701	1	43.701	13.19138	0.00460	4.96460
Within Groups	33.128	10	3.313			
Total	76.829	11				

Table D.3 ANOVA Analyses of S55

a) C-Mw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	18.750	1	18.750	12.90434	0.00491	4.96460
Within Groups	14.530	10	1.453			
Total	33.280	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	13.653	1	13.653	7.16209	0.02324	4.96460
Within Groups	19.063	10	1.906			
Total	32.717	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.403	1	0.403	0.27394	0.61210	4.96460
Within Groups	14.723	10	1.472			
Total	15.127	11				

b) C-Vw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	21.601	1	21.601	6.37788	0.03010	4.96460
Within Groups	33.868	10	3.387			
Total	55.469	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	18.008	1	18.008	5.16245	0.04640	4.96460
Within Groups	34.882	10	3.488			
Total	52.889	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.163	1	0.163	0.28538	0.60487	4.96460
Within Groups	5.723	10	0.572			
Total	5.887	11				

c) C-Flow Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	19.508	1	19.508	15.48010	0.00280	4.96460
Within Groups	12.602	10	1.260			
Total	32.109	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	4.320	1	4.320	4.37838	0.06287	4.96460
Within Groups	9.867	10	0.987			
Total	14.187	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	5.467	1	5.467	4.27093	0.06565	4.96460
Within Groups	12.802	10	1.280			
Total	18.269	11				

Table D.4 ANOVA Analyses of NP20

a) C-Mw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	2.168	1	2.168	1.74493	0.21594	4.96460
Within Groups	12.422	10	1.242			
Total	14.589	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	1.268	1	1.268	0.89125	0.36739	4.96460
Within Groups	14.222	10	1.422			
Total	15.489	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.120	1	0.120	0.09912	0.75936	4.96460
Within Groups	12.107	10	1.211			
Total	12.227	11				

b) CVw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	2.521	1	2.521	13.07260	0.00472	4.96460
Within Groups	1.928	10	0.193			
Total	4.449	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	2.521	1	2.521	13.07260	0.00472	4.96460
Within Groups	1.928	10	0.193			
Total	4.449	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	2.521	1	2.521	6.07674	0.03338	4.96460
Within Groups	4.148	10	0.415			
Total	6.669	11				

c) C-Flow Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.021	1	0.021	0.15684	0.70040	4.96460
Within Groups	1.328	10	0.133			
Total	1.349	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.053	1	0.053	0.16967	0.68909	4.96460
Within Groups	3.143	10	0.314			
Total	3.197	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.008	1	0.008	0.02052	0.88894	4.96460
Within Groups	3.655	10	0.366			
Total	3.663	11				

Table D.5 ANOVA Analyses of NP35

a) C-Mw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.141	1	0.141	0.12840	0.72755	4.96460
Within Groups	10.968	10	1.097			
Total	11.109	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.480	1	0.480	0.52922	0.48362	4.96460
Within Groups	9.070	10	0.907			
Total	9.550	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.101	1	0.101	0.26758	0.61621	4.96460
Within Groups	3.768	10	0.377			
Total	3.869	11				

b) C-Vw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.241	1	0.241	2.53954	0.14211	4.96460
Within Groups	0.948	10	0.095			
Total	1.189	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	2.521	1	2.521	9.68930	0.01101	4.96460
Within Groups	2.602	10	0.260			
Total	5.123	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	1.203	1	1.203	4.41860	0.06186	4.96460
Within Groups	2.723	10	0.272			
Total	3.927	11				

c) C-Flow Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.101	1	0.101	2.28302	0.16173	4.96460
Within Groups	0.442	10	0.044			
Total	0.542	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.853	1	0.853	2.46866	0.14721	4.96460
Within Groups	3.457	10	0.346			
Total	4.310	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.368	1	0.368	0.99819	0.34131	4.96460
Within Groups	3.682	10	0.368			
Total	4.049	11				

Table D.6 ANOVA Analyses of NP55

a) C-Mw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.001	1	0.001	0.00534	0.94321	4.96460
Within Groups	1.562	10	0.156			
Total	1.563	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.301	1	0.301	2.81591	0.12426	4.96460
Within Groups	1.068	10	0.107			
Total	1.369	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.333	1	0.333	3.04878	0.11139	4.96460
Within Groups	1.093	10	0.109			
Total	1.427	11				

b) C-Vw Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.001	1	0.001	0.02762	0.87131	4.96460
Within Groups	0.302	10	0.030			
Total	0.302	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.521	1	0.521	14.95215	0.00313	4.96460
Within Groups	0.348	10	0.035			
Total	0.869	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.563	1	0.563	9.65714	0.01111	4.96460
Within Groups	0.583	10	0.058			
Total	1.147	11				

c) C-Flow Method

ANOVA Mold 1 & Mold 2

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.013	1	0.013	0.13423	0.72172	4.96460
Within Groups	0.993	10	0.099			
Total	1.007	11				

ANOVA Mold 2 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.213	1	0.213	1.91617	0.19639	4.96460
Within Groups	1.113	10	0.111			
Total	1.327	11				

ANOVA Mold 1 & Mold 3

Source	*SS*	*df*	*MS*	*F*	*P-value*	*F criterion*
Between Groups	0.333	1	0.333	1.86567	0.20190	4.96460
Within Groups	1.787	10	0.179			
Total	2.120	11				

APPENDIX E

COMPRESSIVE STRENGTH TEST RESULTS

Table E.1 Compressive Strength Test Results of S20

Compressive	**C-Mw**			**C-Vw**			**C-Flow**		
Strength (MPa)	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3
7-Day	24.8	24.7	28.1	28.1	28.5	29.6	22.5	23.5	24.1
	25.6	25.3	27.4	27.4	30.6	28.8	24.5	23.5	24.0
	24.0	26.2	27.1	30.8	31.3	26.0	23.9	23.9	21.0
	24.1	26.4	25.9	28.4	30.6	28.5	25.1	23.9	21.3
	24.3	26.0	26.3	27.6	31.2	29.4	22.7	22.6	25.1
	24.0	27.3	28.6	31.4	28.7	29.0	23.6	22.1	25.6
Mean	**24.5**	**26.0**	**27.2**	**29.0**	**30.2**	**28.6**	**23.7**	**23.3**	**23.5**
CV (%)	**2.6**	**3.5**	**3.8**	**5.9**	**4.1**	**4.6**	**4.3**	**3.2**	**8.2**
28-Day	41.0	38.6	41.3	38.8	43.3	36.4	35.4	38.5	37.9
	37.0	38.7	40.3	36.2	38.6	37.5	37.7	39.3	37.6
	40.1	38.8	40.6	40.7	41.9	35.4	38.1	41.9	36.4
	38.3	37.7	42.6	40.6	40.7	40.1*	35.4	38.0	37.5
	39.1	39.7	39.6	41.0	38.0	33.8	37.7	35.1	37.0
	40.0	40.7	39.8	35.8	40.6	33.5	36.5	36.1	38.0
Mean	**39.3**	**39.0**	**40.7**	**38.9**	**40.5**	**35.3**	**36.8**	**38.2**	**37.4**
CV (%)	**3.7**	**2.7**	**2.7**	**6.0**	**4.9**	**4.8**	**3.3**	**6.3**	**1.6**

** denotes the outliers of molds, underlined numbers denotes the outliers of methods*

Table E.2 Compressive Strength Test Results of S35

Compressive Strength (MPa)	**C-Mw**			**C-Vw**			**C-Flow**		
	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3
7-Day	22.5	22.2	21.8	25.9	26.1	23.1	21.6	22.9	19.0
	21.4	21.4	22.7	24.9	26.5	22.9	22.2	23.5	18.0
	22.9	21.4	22.9	25.4	25.1	22.8	22.4	22.6	19.6
	20.2	21.2	23.1	26.0	25.3	24.1	21.4	21.5	21.1
	19.3	21.3	23.8	25.6	25.9	22.0	20.3	24.2	18.3
	20.9	21.1	21.1	24.7	25.9	22.9	21.2	22.6	20.0
Mean	**21.2**	**21.4**	**22.6**	**25.4**	**25.8**	**23.0**	**21.5**	**22.9**	**19.3**
CV (%)	**6.4**	**1.8**	**4.3**	**2.1**	**2.0**	**2.9**	**3.5**	**4.0**	**5.9**
28-Day	42.1	38.4	43.7	46.1	41.8	41.0	38.3	40.0	40.6
	43.7*	37.5	42.8	44.4	39.2	41.9	37.4	36.9	40.1
	34.6*	40.2	45.5	44.9	42.4	40.8	32.9	35.8	41.4
	38.9	40.8	42.6	42.7	40.7	43.1	34.4	38.5	37.9
	37.3	33.9*	44.6	43.2	42.9	40.5	37.9	38.7	41.4
	40.1	38.6	45.3	44.3	40.9	42.8	37.7	35.7	40.1
Mean	**39.6**	**39.1**	**44.1**	**44.3**	**41.3**	**41.7**	**36.4**	**37.6**	**40.3**
CV (%)	**5.1**	**3.5**	**2.8**	**2.7**	**3.2**	**2.6**	**6.1**	**4.6**	**3.2**

** denotes the outliers of molds, underlined numbers denotes the outliers of methods*

Table E.3 Compressive Strength Test Results of S55

Compressive Strength (MPa)	C-Mw			C-Vw			C-Flow		
	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3
7-Day	15.5	17.4	16.7	17.8	17.5	17.0	14.4	14.0	14.9
	16.8	16.2	16.8	17.0	18.2	17.9	15.4	13.9	14.7
	16.5	16.0	15.2	17.9	16.9	18.5	15.2	13.6	14.9
	16.0	17.5	16.3	18.2	17.6	17.5	14.0	14.0	14.4
	16.5	18.1	16.5	17.4	17.5	17.8	14.4	13.1	14.8
	16.0	16.1	15.7	18.5	17.4	17.7	14.5	14.0	14.1
Mean	**16.2**	**16.9**	**16.2**	**17.8**	**17.5**	**17.7**	**14.7**	**13.8**	**14.6**
CV (%)	**2.9**	**5.3**	**3.9**	**3.0**	**2.4**	**2.8**	**3.7**	**2.6**	**2.2**
28-Day	32.6	30.6	34.1	39.4	38.3	40.2	32.3	33.4	32.3
	33.3	33.8	32.8	39.6	36.5	39.8	31.3	33.8	33.3
	34.5	29.9	35.3	40.6	35.5	39.4	30.4	36.1	32.3
	35.0	31.8	32.4	38.8	39.7	38.0	30.3	33.9	32.4
	35.2	32.4	32.6	38.7	32.6*	39.4	32.3	33.7	33.0
	34.3	31.4	35.5	39.6	38.0	38.5	33.5	34.5	34.9
Mean	**34.2**	**31.7**	**33.8**	**39.5**	**37.6**	**39.2**	**31.7**	**34.2**	**33.0**
CV (%)	**3.0**	**4.3**	**4.1**	**1.7**	**4.3**	**2.1**	**3.9**	**2.9**	**3.0**

** denotes the outliers of molds, underlined numbers denotes the outliers of methods*

Table E.4 Compressive Strength Test Results of NP20

Compressive Strength (MPa)	C-Mw			C-Vw			C-Flow		
	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3
7-Day	29.2	28.9	29.1	26.0	26.0	26.1	21.8	20.9	20.7
	29.5	29.0	29.6	26.3	26.2	26.1	21.6	20.8	20.6
	28.9	28.9	30.3	25.9	25.9	26.3	21.1	21.1	21.0
	28.7	28.7	30.0	26.6	25.7	26.4	20.9	20.8	20.4
	28.8	28.8	28.3	26.3	26.5	25.7	21.2	20.7	21.5
	29.5	29.5	28.8	26.2	26.0	25.8	21.2	21.0	21.6
Mean	**29.1**	**29.0**	**29.4**	**26.2**	**26.1**	**26.1**	**21.3**	**20.9**	**21.0**
CV (%)	**1.2**	**1.0**	**2.6**	**0.9**	**1.1**	**1.0**	**1.6**	**0.7**	**2.3**
28-Day	39.7	40.7	43.3	39.2	39.0	39.7	33.8	33.4	<u>34.7</u>
	41.3	43.2	41.2	38.1	39.1	40.1	33.7	33.0	33.5
	41.1	41.2	41.9	37.8	38.8	39.8	33.3	33.6	33.3
	42.6	43.3	42.3	38.5	39.1	38.6	32.6	33.0	32.8
	42.2	43.5	39.8	38.2	39.8	38.7	33.2	32.9	32.6
	41.7	41.8	41.3	37.9	39.4	38.3	33.2	33.4	33.2
Mean	**41.4**	**42.3**	**41.6**	**38.3**	**39.2**	**39.2**	**33.3**	**33.2**	**33.4**
CV (%)	**2.5**	**2.9**	**2.8**	**1.3**	**0.9**	**1.9**	**1.3**	**0.9**	**2.2**

** denotes the outliers of molds, underlined numbers denotes the outliers of methods*

Table E.5 Compressive Strength Test Results of NP35

Compressive Strength (MPa)	C-Mw			C-Vw			C-Flow		
	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3
7-Day	20.3	21.2	21.5	17.1	17.2	18.2	14.6	14.7	14.9
	20.4	21.6	21.9	17.6	17.3	18.7	14.9	14.8	15.4
	21.5	21.4	21.8	17.2	17.5	16.0	15.0	14.4	18.8
	22.6	21.2	21.9	17.8	17.6	18.0	14.4	14.2	15.2
	20.7	21.0	22.3	17.4	17.4	18.4	14.2	14.1	15.4
	21.2	20.4	21.3	17.6	17.6	16.0	14.0	14.5	14.4
Mean	**21.1**	**21.1**	**21.8**	**17.5**	**17.4**	**17.6**	**14.5**	**14.5**	**15.7**
CV (%)	**4.1**	**2.0**	**1.6**	**1.5**	**0.9**	**7.0**	**2.7**	**1.9**	**10.0**
28-Day	34.4	34.0	34.8	29.9	28.9	29.2	25.5	24.9	25.4
	33.6	33.1	34.5	29.5	28.8	29.5	25.1	24.9	25.0
	35.6	35.8	34.5	29.4	29.6	29.8	25.4	24.8	25.3
	35.4	36.0	33.6	29.2	29.1	30.2	25.2	25.0	24.5
	34.6	36.1	34.6	29.0	29.1	31.1	24.8	25.2	26.8
	34.2	34.1	34.7	29.1	28.9	30.1	25.0	25.1	26.1
Mean	**34.6**	**34.9**	**34.5**	**29.4**	**29.1**	**30.0**	**25.2**	**25.0**	**25.5**
CV (%)	**2.2**	**3.7**	**1.3**	**1.1**	**1.0**	**2.2**	**1.0**	**0.6**	**3.2**

** denotes the outliers of molds, underlined numbers denotes the outliers of methods*

Table E.6 Compressive Strength Test Results of NP55

Compressive	**C-Mw**			**C-Vw**			**C-Flow**		
Strength (MPa)	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3	Mold-1	Mold-2	Mold-3
7-Day	10.9	11.3	12.2	8.3	8.2	8.5	7.2	7.1	7.7
	11.1	11.1	11.7	8.0	8.3	8.7	7.2	7.1	7.8
	11.1	10.7	12.3	7.8	8.2	8.9	7.3	7.1	7.8
	11.6	11.4	11.5	7.9	8.4	8.8	7.2	7.1	7.6
	11.9	11.0	11.7	8.2	8.1	8.0	7.0	7.1	7.6
	11.5	11.3	12.1	8.1	8.3	8.7	7.2	7.2	7.7
Mean	**11.4**	**11.1**	**11.9**	**8.1**	**8.3**	**8.6**	**7.2**	**7.1**	**7.7**
CV (%)	**3.3**	**2.3**	**2.7**	**2.3**	**1.3**	**3.7**	**1.4**	**0.6**	**1.2**
28-Day	21.1	21.4	21.2	16.5	16.0	16.7	14.6	14.6	15.3
	20.4	21.0	21.1	16.0	16.1	16.4	15.1	14.8	15.1
	21.2	21.2	21.8	16.1	16.2	16.4	14.2	14.9	14.6
	21.6	20.7	21.5	15.8	16.1	16.2	14.7	15.0	14.9
	20.9	21.6	21.4	16.2	16.2	16.8	15.3	15.1	15.2
	21.2	20.6	21.4	16.1	16.2	16.8	15.1	15.0	15.9*
Mean	**21.1**	**21.1**	**21.4**	**16.1**	**16.1**	**16.6**	**14.8**	**14.9**	**15.0**
CV (%)	**1.9**	**1.9**	**1.1**	**1.4**	**0.5**	**1.5**	**2.8**	**1.2**	**1.8**

** denotes the outliers of molds, underlined numbers denotes the outliers of methods*