EFFECTS OF POZZOLAN INCORPORATION AND CURING CONDITIONS ON STRENGTH AND WATER RESISTANCE OF NATURAL GYPSUM PASTES

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ABSTRACT

EFFECTS OF POZZOLAN INCORPORATION AND CURING CONDITIONS ON STRENGTH AND WATER RESISTANCE OF NATURAL GYPSUM PASTES

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There are large reserves of gypsum rock ($CaSO_4 \cdot 2H_2O$) in Turkey and in various regions of the world. Heating gypsum rock to 140 - 190 ^{0}C causes it to lose three-fourths of its water molecules and turn into gypsum, called plaster of Paris; heat application over 190 ^{0}C results in loss of all the water molecules and this form of the material is called gypsum anhydrite.

When gypsum is mixed with water, it gains cementitious property and hardens in a short time. Therefore, natural gypsum anhydrite and especially plaster of Paris are widely used in the construction industry. On the other hand, its not being water resistant and having low strength restrict the use of gypsum products for outdoor applications.

In this study, the effects of pozzolan incorporation to natural gypsum pastes and application of various curing regimes for improving their water resistance and strength were investigated. Compressive strength and absorption tests on one thousand one hundred twenty two 5-cm cube specimens produced from

13 different mixture types were conducted. Also the microstructures of these products were investigated using the analytical technique X-Ray Diffraction.

The test results showed that water resistance and strength properties of pozzolan-incorporated gypsum products were improved. Curing of the product at elevated temperature regimes was an additional factor that contributed to this improvement. It was concluded that the natural gypsum mixtures prepared and cured at the above-mentioned conditions could also be used for outdoor applications.

Keywords: Pozzolan, Natural Gypsum, Elevated Temperature Curing

ÖZ

PUZOLAN KATILMASININ VE KÜR KOŞULLARININ DOĞAL ALÇI HAMURLARININ DAYANIMLARINA VE SUYA DAYANIKLILIĞINA ETKİLERİ

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Türkiye'de ve dünyanın birçok bölgesinde çok büyük miktarlarda doğal alçıtaşı rezervi bulunmaktadır. Alçıtaşının 140 - 190 ^{0}C arasında pişirilmesiyle bu malzeme, içerdiği su moleküllerinin dörtte üçünü kaybederek normal alçı (hemihidrat) durumuna dönüşmektedir; 190 ^{0}C ve üstündeki sıcaklıklarda ise içerdiği suyun tamamını kaybetmekte ve malzemenin bu hali susuz alçı (hidrate alçı) olarak adlandırılmaktadır.

Alçı, su ile birleştirildiğinde, bağlayıcılık özelliği kazanarak kısa sürede sertleşmektedir. O bakımdan, susuz alçı ve özellikle de doğal alçı yapı endüstrisinde çokça kullanılmaktadır. Öte yandan, alçılı ürünlerin suya karşı dayanıklı olmayışları ve düşük dayanımları, bu ürünlerin dış cephede de kullanımını sınırlamaktadır.

Bu çalışmada, doğal alçıya puzolan katımının ve değişik kür rejimleri uygulanmasının bu ürünlerin suya dayanıklılıkları ve dayanımları üzerindeki etkileri araştırılmıştır. 13 değişik tip karışımdan bin yüz yirmi iki adet 5-cm'lik küpler hazırlanarak basınç dayanımı ve su emme deneyleri yapılmıştır. Ayrıca, X-Işını Difraktometre (XRD) analitik yöntemiyle, mikroyapıları araştırılmıştır.

Deneyler sonucunda, puzolan içeren alçı karışımlarının suya dayanıklılık ve dayanım özelliklerinde gelişme kaydedilmiştir. Yüksek sıcaklıkta kür uygulaması bu gelişmeye ayrıca katkı sağlayan bir faktör olmuştur. Sonuç olarak, yukarıda bahsedilen tarzda hazırlanan ve kür edilen doğal alçı karışımlarının dış cephelerde de kullanılabileceği görülmüştür.

Anahtar Kelimeler: Puzolan, Doğal Alçı, Yüksek Sıcaklık Kürü

To My Parents

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The author wishes to express his deepest gratitude to Prof. Dr. Turhan Y. Erdoğan for suggesting such an investigation on increasing the strength and water-resistance of pastes made with natural gypsum so that gypsum could also be used for outdoor applications, and who supervised the work for a long time even after his retirement.

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CHAPTER 1

INTRODUCTION

1.1 General

Gypsum is a binding material that is usually obtained by heating and driving off some or all of the crystallization water present in the structure of gypsum rock*. Mineral gypsum also occurs in the form of gypsite or gypsum earth.

When gypsum rock (calcium sulfate dehydrate -- $CaSO_4 \cdot 2H_2O$) is heated, depending on the degree of the temperature it is subjected to, either partial or complete dehydration occurs:

Partial dehydration takes place when gypsum rock is heated to a temperature not in excess of 190 - 200 ^{0}C. The necessary temperature to cause partial dehydration is usually between 140 - 190 ^{0}C, although dehydration starts after 100 ^{0}C. So, when gypsum rock partially dehydrates, it loses 3/4 of its water of crystallization and a product having calcium sulfate and half a molecule of

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*For the last forty years, gypsum has also been produced artificially as "phosphogypsum", which is the major by-product of wet-process phosphoric acid production, or as "desulfogypsum", obtained from the desulfurization of combustion gases in coal burning power plants which are utilized for generation of electricity. The use of by-product gypsum is similar to that of natural gypsum.

water ($CaSO_4.1/2H_2O$) is obtained. This product is called “hemihydrate gypsum”, or “plaster of Paris”.

Complete dehydration takes place when gypsum rock is heated to temperatures in excess of 190 - 200 ^0C. In such a case, the gypsum rock loses all of its crystallization water and the product $CaSO_4$ is obtained, which is called “gypsum anhydrite”.

In short, dehydration of gypsum rock is generally indicated by the following equations:

$$CaSO_4.2H_2O \xrightarrow{100\ ^0C\ -\ 190\ ^0C} CaSO_4.1/2H_2O + 3/2H_2O$$

plaster of Paris

$$CaSO_4.2H_2O \xrightarrow{\text{above } 190\ ^0C} CaSO_4 + 2H_2O$$

gypsum
anhydrite

Whether it is in hemihydrate or anhydrite form the product obtained as gypsum possesses binding potential. When gypsum is mixed with water, a plastic (shapeable) paste is obtained which sets (gains rigidity) and hardens as time passes.

The setting and hardening of the gypsum produced in hemihydrate form ($CaSO_4.1/2H_2O$) takes place when this material combines with 3/2 molecules of water upon being mixed with water and turns to $CaSO_4.2H_2O$ form. Similarly, the setting and hardening of the gypsum produced in anhydrite form

($CaSO_4$) takes place when this material combines with 2 molecules of water upon being mixed with water and turns to $CaSO_4.2H_2O$ form.

The reactions in setting and hardening of gypsum paste are indicated by the following equations:

$$CaSO_4.1/2H_2O + 3/2H_2O \longrightarrow CaSO_4.2H_2O$$

plaster of Paris

$$CaSO_4 + 2H_2O \longrightarrow CaSO_4.2H_2O$$

gypsum
anhydrite

Gypsum is one of the oldest materials that human beings have used for construction purposes. It still is widely used as a construction material, such as [1]:

- For making casts and architectural adornments

  This is due to the fact that gypsum expands 2-3 times upon hardening and produces a clear impression of the mold.

- In making gypsum plasters

  Gypsum plasters find their principal application as wall covering. Plasters are also cast into building blocks for the construction of partition walls and roofings, or for covering. The gypsum cast into building blocks can easily be lifted and applied on walls or ceilings, and results in lower dead load on them, also having higher sound absorption.

- For providing protection of some metallic elements in a structure against fire

Although plasters based on lime and cement are also used widely, gypsum has become the most important binder in the last 40 years.

The main advantages of gypsum plasters can be cited as follows [2]:

- Their setting time can be precisely controlled according to function.
- Time delay between successive coats may be very small.
- Unlike cement-based plasters, they are non-shrinking, provided that plastering technique is correct.
- They have excellent fire resistance.

  The water of crystallization in set gypsum plasters vaporizes slowly in a fire. This process absorbs considerable heat minimizing the rate of temperature rise in and behind the plaster. The gypsum calcined in this way acts as an efficient insulating barrier against fire.

Despite its numerous beneficial uses listed above, gypsum is still not a material as widely used as it should be. Its use to a greater extent is hindered by its having relatively higher porosity and by its being a non-hydraulic binder.

Gypsum paste is not a water resistant material because of its solubility (2g/lt)

[3, 4, 5]. Therefore, gypsum products are generally used in the building industry as a surface finish on interior walls and in the production of dry-wall products for interior lining and partitioning.

1.2 Object and Scope

The objective of this study was to investigate some means for obtaining gypsum pastes that would have higher water resistance and higher strength so that they could also be used for outdoor applications; thus to allow this material to be used to a greater extent.

To fulfill the objective mentioned above, it was planned to incorporate pozzolanic materials into gypsum pastes and subject them to different curing regimes.

13 different groups of mixes were planned to be used for such an investigation:

- Six different mixes were prepared by including 0, 15, 30, 45, 60, and 75 percent (by weight) fly ash in gypsum pastes,

- Five different groups of mixes were prepared by including 15, 30, 45, 60, and 75 percent (by weight) blast-furnace slag in gypsum pastes.

- For comparing the properties of the above-mentioned 11 mixes that contain pozzolanic materials with those that contain no gypsum, one mixture was made using only fly ash and another, using only slag.

With the intention of having a satisfactory pozzolanic reaction, all mixes which contained either fly ash or slag were made including 40 percent hydrated lime by weight of the pozzolanic material used*.

The pastes were prepared using a “water/binder” ratio of 0.6.

A total of 1053 of 5-cm cube specimens were cast and cured at different conditions to study the effects of pozzolanic inclusion and the curing regimes applied, on the strengths of these specimens.

Another 69 cube specimens were cast to study their water absorption characteristics.

In addition to these above-mentioned studies, the microstructures of the mixtures were investigated by using X-Ray Diffraction (XRD).

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*For example, for a mix containing 15 percent pozzolanic material inclusion by weight actually consisted of 85 units gypsum, 15 units pozzolanic material, and 15*0.4 = 6 units lime. By considering the total weight of the mix as 100 units, the mix actually contains 80.19 percent gypsum, 14.15 percent pozzolanic material and 5.66 percent lime by weight.

CHAPTER 2

A BRIEF REVIEW OF THE PROPERTIES OF GYPSUM AND THE TWO POZZOLANIC MATERIALS: FLY ASH AND BLAST-FURNACE SLAG

In this study, effects of pozzolanic material addition to gypsum on the strength and water resistance of gypsum pastes are investigated. The two different types of pozzolanic materials to be used were chosen as fly ash and blast-furnace slag. Therefore, it is believed that a brief review of the properties of gypsum and the two types of pozzolans used is considered to be appropriate to explain the reasons for their incorporation in gypsum pastes in such an investigation.

2.1 Properties of Gypsum Pastes and Mortars

Setting time, plasticity, strength and fireproofing are the most important properties of gypsum pastes and mortars [1].

Setting Time -- The length of time between the moment that the gypsum and water are mixed until the attainment of rigidity is called the setting time. Since the mixture can be shaped during the time it is still plastic, setting time is important for the convenient use of the material.

The time required for neat gypsum paste (with no admixture) to set is normally about 30 minutes. The setting time for pastes made of anhydrous gypsum or pastes containing some impurities can be much longer.

The setting time of gypsum can be extended by the inclusion of set retarding materials; the setting time can be shortened by the use of set accelerating materials. The materials mainly used as retarders or accelerators can be given as follows [1]:

Set retarders -- Borax, tartaric acid, organic materials derived from keratin, glue, sawdust, and blood are materials used as retarders. The amount of retarder required does not exceed 0.2 %.

Set accelerators -- Salts, alum, sodium sulfate, zinc sulfate and potassium sulfate are used accelerators.

Plasticity -- Plastic gypsum mortars are those materials that can be easily shaped or easily spread. For convenient use, these materials should not be too sticky or too stiff.

The plasticity of the gypsum mortar is largely affected by the amount of water in the mix; gypsum mortars become more plastic when higher amounts of water are used.

The plasticity is also affected by the amount of sand that is added to gypsum paste to obtain gypsum mortar. Inclusion of sand reduces the stickiness of the paste. However, if too much sand is added, the mortar becomes less workable. Approximately, 2/3 by weight of the mixture is constituted of sand in gypsum mortars. The plasticity of gypsum can also be increased by the inclusion of hydrated lime.

Strength -- The compressive strengths of gypsum plasters and mortars are much higher (approximately 3 or more times greater) than their tensile strengths.

The ultimate strength of gypsum pastes and mortars depends upon the following factors:

- The water/gypsum ratio:

  When gypsum and water are mixed, gypsum uses just the right amount of water needed for the chemical reaction for the reformation of $CaSO_4.2H_2O$. If the water/gypsum ratio is high, then the amount of water leaving the mixture by evaporation will be high. Thus there will be more voids left behind which will lead to lower strength. A water/gypsum ratio of 0.6 is approximately the lowest ratio at which the material is plastic enough to be shaped.

- The amount of sand used in the mortar:

  Although the use of sand is beneficial to reduce the stickiness and improve plasticity of the gypsum mortar, the amount of sand used in a gypsum mixture should not be too high. The higher the amount of sand in a mortar the lower is the amount of the paste. Therefore, addition of higher amounts of sand decreases the strength. A mortar containing two parts of sand to one part of paste has about 60% of the ultimate strength of a mix made without sand.

  On the other hand, if no sand or very little is added, then the material may show a lot of shrinkage upon drying, leading to cracks. Thus very low strength may be obtained.

The tensile strength of gypsum pastes or mortars can be improved by the inclusion of certain materials in the mixture. Inclusion of a small amount of hair, wood fiber, or asbestos fiber results in better cohesion and higher tensile strength.

Fireproofing -- Gypsum products are useful as fireproofing. The surface is decomposed at temperatures exceeding 100 ^{o}C, and forms a powder. This powder covering the surface acts as an effective insulator.

2.2 Pozzolanic Materials

According to ASTM C 125 [6], pozzolans are “siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties”.

The activity of a pozzolanic material with hydrated lime, that is, how well a pozzolan will behave in a mortar or concrete, is expressed as its ”pozzolanic activity”. In other words, “pozzolanic activity” refers to the reaction of alumino-silicates with calcium hydroxides to form cementitious products [7].

When finely divided pozzolans are brought into contact with calcium hydroxide in the presence of moisture, some chemical reactions start to take place at ordinary temperatures.

Calcium silicate hydrate is the main product of lime - pozzolan reaction. Calcium aluminohydrate,hydrated gehlenite, calcium carboaluminate, ettringite and calcium alumino monosulfate are some of the other products that result from the lime pozzolan reaction in addition to calcium silicate hydrate [7, 8]. As a result, chemical compounds possessing hydraulic cementitious properties are formed.

The main chemical reaction between the silica of the finely divided pozzolan and calcium hydroxide in the presence of moisture can be simply shown as follows:

Calcium Hydroxide + Silica + Water → Calcium Silicate
(CH)* (S) (H) Hydrate (C-S-H)

Calcium silicate hydrate is the hydration product in very finely divided state and because of its extraordinarily high surface area, it provides a binding property.

Pozzolans are generally grouped as “natural pozzolans” and “artificial pozzolans” [7, 9, 10, 11].

Natural pozzolans are the naturally occurring materials such as volcanic ashes, volcanic glasses, volcanic tuffs, thermally treated clays and shales, and diatomaceous earths. Artificial pozzolans are industrial by-products such as fly ashes, silica fumes, and granulated blast furnace slags.

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*C, H and S are the abbreviations used as in cement chemistry : $C=CaO$, $H=H_2O$, and $S=SiO_2$.

2.2.1 Natural Pozzolans

Natural pozzolans are the naturally occurring siliceous or siliceous and aluminous materials which in themselves possess little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. These are the pozzolanic materials other than those obtained as industrial by-products. Volcanic glasses, volcanic tuffs, trasses, diatomaceous earths and some clays and shales possess pozzolanic properties when they are in finely divided form [7].

There is no classification of natural pozzolans in the national specifications. However, some researchers have made certain proposals for the classification of these materials according to their activities and origins [13, 14]. While materials of volcanic origin have pozzolanic properties in a raw state, as they are found in nature, some clays and shales need to be processed by thermal treatment to acquire satisfactory pozzolanic properties. Therefore, it would be appropriate to consider natural pozzolans under two main groups [7]:

- Natural pozzolans of volcanic origin, and
- Thermally treated clays, shales, and diatomaceous earths.

2.2.1.1 Physical Properties of Finely Divided Natural Pozzolans

Natural pozzolans have to be ground to a suitable fineness before they are used. Fineness, strength activity index, water requirement, soundness, and uniformity are the important physical properties to be investigated.

Fineness -- Finely divided natural pozzolans should have a suitable fineness in order to possess pozzolanic reactions in the in the presence of moisture and calcium hydroxide. According to ASTM Standards, fineness of finely divided natural pozzolans is determined by wet sieving on a 45μm sieve and the maximum amount retained on this sieve should not be greater than 34% [14].

Density -- Normally, the density of finely divided natural pozzolans for use as mineral admixture ranges from 2.1 to 2.8 g/cm^3.

Strength activity index -- Strength activity index of a finely divided natural pozzolans indicates its capacity to perform the pozzolanic reactions and its rate of strength development. Strength activity index of finely divided pozzolans is determined according to ASTM C 311 [16]. According to ASTM C 618 [14], this value should not be less than 75% of the control mixture.

Water requirement -- Water requirement of finely divided pozzolans is determined according to ASTM C 311 [15]. According to ASTM C 618 [14], this value should not be more than 115% of the control mixture.

Soundness -- ASTM C 618 [14] limits the maximum percentage of expansion or contraction of mixtures containing natural pozzolans as 0.8.

Uniformity -- The uniformity of an individual sample of pozzolan is checked by determining its fineness and its density. According to ASTM C 618 [14], the density and fineness of individual samples should not vary by more than 5% from the average established by ten preceeding tests, or by all tests if the number is less than ten.

2.2.1.2 Composition and Chemical Properties of Natural Pozzolans

More than 80 percent of most natural pozzolans contain chemical compounds formed from silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO). In addition to these oxides, some small percentages of magnesium oxide (MgO), and alkalies (Na_2O and K_2O) are found in natural pozzolans. Table 2.1 shows the oxide composition of some well-known natural pozzolans [16].

In natural pozzolans, the content of silica (SiO_2) + alumina (Al_2O_3) + iron oxide (Fe_2O_3) affects the pozzolanic activity of natural pozzolans greatly. These oxides play an important role in the occurrence of pozzolanic reactions. Also, the moisture content of finely divided natural pozzolans should not be more than 3% and the loss on ignition in natural pozzolans should not be more than 10% [14].

Table 2.1 Oxide Composition of Some Natural Pozzolans, % [7]

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Volcanic Glass:							
Bacoli (Italy)	53.1	18.2	4.3	9.0	1.2	3.1	7.6
Santorin Earth (Greece)	65.1	14.5	5.5	3.0	1.1	2.6	3.9
Volcanic Tuffs:							
Rheinish Trass (Germany)	52.1	18.3	5.8	4.9	1.2	1.5	5.1
Segni-Latium (Italy)	45.5	19.6	9.9	9.3	4.5	0.9	6.4

(continuing)

Table 2.1 (continued) [7]

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
Diatomites:							
Diatomaceous Earth (California)	86.0	2.3	1.8	-	0.6	0.4	-
Calcined Clay: Handelage (Germany)	42.2	16.1	7.0	21.8	1.9	0.3	1.0

2.3 Fly Ash

In most thermal power plants, pulverized coal is burned to produce energy for generation of electricity. The fine coal powder, crushed to a fineness of 80 percent passing a 75μm (No.200) sieve, is mixed with preheated air and blown into the boilers for combustion [17]. As a result of this coal burning, various gases and some wastes (coal ashes as non-combustible residue) with different properties are produced.

The principal part of (about 75 or 80 percent) of the wastes produced by burning pulverized coal in thermal power plants are those ashes in very small particles which are carried upwards or which fly out of the combustion chamber with the flue gases [18]. Their escape from the stack into the air is prevented by electrostatic precipitators, which is the most common method, or by some other collection methods such as by fabric bag filters. In modern power plants, over 99 percent of this fine, lighter weight ash is removed before the gas goes out of the stack [18].

Fly ash is the finely divided residue or the very fine ash resulting as a by-product form the combustion of powdered coal in the power plants for providing the energy for electricity and transported from the firebox through the boiler by flue gases into precipitators [7]. In some countries, such as the United Kingdom, this by-product is known as “pulverized fly ash”, pfa.

Fly ashes exhibit pozzolanic properties. In themselves, they possess little or no cementitious value but in the presence of moisture they react chemically with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties.

2.3.1 Classes of Fly Ashes

Traditionally, even though the fly ash constituents are not present as oxides, fly ashes are classified in accordance with their oxide compositions [10]. In some countries, such as France and Spain, where there is no fly ash standard, lime and sulfate content are taken into account to identify fly ashes [19].

While there is no classification of fly ashes in the specifications of most countries, fly ashes are classified into two broad categories, Class F and Class C, by ASTM C 618 [14], depending on their chemical composition and the type of coal they are obtained from. Table 2.2 shows the classes of fly ashes and other pozzolans.

Fly ashes having a CaO content of less than 10% are recognized as low-lime fly ashes while those having a CaO content higher than 10% are known as high-lime fly ashes.

Table 2.2 Classes of Fly Ash and Other Pozzolans in ASTM C 618 [14]

Class	Description
F	Content of silica (SiO_2)+ alumina (Al_2O_3)+ iron oxide (Fe_2O_3)$\geq$70%; fly ash produced from anthracite or bituminous coal; have pozzolanic properties only.
C	Content of silica (SiO_2)+ alumina (Al_2O_3)+ iron oxide (Fe_2O_3)$\geq$50%; fly ash produced from lignite or subbituminous coal; may have a lime content higher than 10%; have pozzolanic and cementitious properties.
N	Natural pozzolans such as diatomaceous earths, opaline cherts and shales, tuffs, volcanic ashes or pumicites, some clays and shales requiring calcination

2.3.2 Physical Properties of Fly Ashes

Physical and chemical properties of fly ashes vary considerably between power plants. Causes of variations may be found in the composition of the coal, the degree of pulverization of the coal, the rate and efficiency of combustion, the type of combustion equipment and the fly ash collection system [20].

According to ASTM C 618 [14] fineness, strength activity index, water requirement, soundness, uniformity, and moisture content are the important physical properties to be investigated.

Particle shape and size -- Fly ash consists of predominantly solid and some hollow particles of spherical shape [20]. Particle size of fly ash ranges from 1 to 150 μm, the majority (75 percent or more) being less than 45 μm (No.325 sieve) [14].

Fineness of fly ash affects the rate of pozzolanic activity and the workability. Generally, use of fly ash normally decreases the water content and improves workability of concrete but an ash with very high fineness may require an increase in water [14].

Density -- Normally, the density of fly ash ranges from 2.1 to 2.7 (average 2.4) g/cm^3.

Color -- Normally, fly ash has a grayish color, when it is in bulk. However, its color may range from light tan to dark gray depending on the type and quality of the coal and on the boiler operation [7].

Strength activity index -- Strength activity index of a fly ash indicates its capacity to perform the pozzolanic reactions and its rate of strength development. Strength activity index of fly ashes is determined according to ASTM C 311 [15]. According to ASTM C 618 [14], this value should not be less than 75% of the control mixture.

Water requirement-- Water requirement of fly ash is affected by the fineness of its particles. The small size and essentially spherical form of the particles usually cause a reduction in the water content of the mixture where the fly ash is used. Water requirement of fly ash is determined according to ASTM C 311 [15]. According to ASTM C 618 [14], this value should not be more than 115% of the control mixture.

Soundness-- ASTM C 618 [14] limits the maximum percentage of expansion or contraction of mixtures containing natural pozzolans as 0.8. The test is conducted in accordance with test method mentioned in ASTM C 311 [15].

Uniformity-- The uniformity of a fly ash is checked by determining its fineness and its density. According to ASTM C 618 [14], the density and fineness of individual samples should not vary by more than 5% from the average established by ten preceeding tests, or by all tests if the number is less than ten.

2.3.3 Composition and Chemical Properties of Fly Ashes

More than 85 percent of most fly ashes contain chemical compounds formed from silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and calcium oxide (CaO). In addition to these oxides, some small percentages of magnesium oxide (MgO), sulfur trioxide (SO_3), and alkalies (Na_2O and K_2O) are found in fly ashes. Carbon particles (C), that is the unburned coal particles collected with fly ash, may also occur as an important ingredient of some fly ashes. Table 2.3 gives the ranges of values for chemical properties obtained by analyzing 13 different class F fly ashes and 9 different class C fly ashes [21].

In fly ashes, the content of silica (SiO_2) + alumina (Al_2O_3) + iron oxide (Fe_2O_3) affects the pozzolanic activity of fly ashes greatly. These oxides play an important role in the occurrence of pozzolanic reactions. As is shown in Table 2.2, the minimum values for the some of these three ingredients required for Class F and Class C fly ashes are 70% and 50% respectively.

Table 2.3 Ranges of Chemical Properties of Fly Ashes from Different Coal Burning Power Plants [22]

Chemical Properties	Class F (less than 10% CaO)	Class C (more than 10% CaO)
SiO_2	43.6 - 64.4	23.1 - 50.5
Al_2O_3	19.6 - 30.1	13.3 - 21.3
Fe_2O_3	3.8 - 23.9	3.7 - 22.5
CaO	0.7 - 6.7	11.5 - 29.0
MgO	0.9 - 1.7	1.5 - 7.5
Na_2O	0 - 2.8	0.4 - 1.9
C, (LOI)*	0.4 - 7.2	0.3 - 1.9

*LOI = Loss on ignition

The amount of calcium oxide (CaO) occurring in a fly ash depends on the type of coal used in power plants. While fly ashes produced from bituminous coal have a CaO content of less than 10%, those produced from subbituminous coals usually contain more than 10% of CaO. Due to the presence of a relatively high amount of CaO (more than 10% of CaO), these fly ashes called high-lime fly ashes possess some cementitious properties in addition to their pozzolanic properties [7].

The magnesium oxide (MgO) content, sulfur trioxide (SO_3) content and alkalies as Na_2O in fly ashes are limited for usages in concrete according to ASTM C 618 [14] as 5%, 5% and 1.5%, respectively. Also, the moisture content of fly ashes should not be more than 3% and the loss on ignition in fly ashes should not be more than 6% [14].

2.4 Blast-Furnace Slag

Iron ores consist essentially of compounds of iron, usually iron oxides such as hematite (Fe_2O_3), magnetite (Fe_3O_4), limonite ($Fe_3O_4.nH_2O$) and siderite ($FeCO_3$); these ores also contain some silica, clay etc., called gangue.

In order to extract the iron from its ore, or in other words, to remove the oxygen of iron oxide and to remove the associated gangue, the ore is heated in a furnace called a blast-furnace to a high temperature under strongly reducing conditions in the presence of a flux. Coke is the most commonly used fuel for the blast-furnace. The fuel for the blast-furnace serves as a reducing agent as well as a source of heat. The carbon from the coke chemically reacts with the oxygen of the iron oxide causing the formation of carbon monoxide and carbon dioxide gases that leave the furnace; thus, what is left behind in the blast-furnace is the molten iron together with such elements as carbon, silicon, alumina, manganese, phosphorus and sulfur which are present in small amounts either as burden in the ore or in the fuel used in melting [7].

The flux (usually limestone as the most common form of basic flux) combines with the gangue of the ore and ash of the fuel, producing a nonmetallic melt called “slag”. Molten iron collects in the bottom of the furnace and the liquid iron blast-furnace slag floats on the pool of iron because of the difference between the densities of these materials. Molten iron and liquid slag are tapped off separately from the furnace.

Blast-furnace slags comprise compounds formed mainly of silica (SiO_2), alumina (Al_2O_3) and lime (CaO). Besides these, slags contain some small percentages of iron oxide (Fe_2O_3), magnesium oxide (MgO), manganese oxide (MnO) and sulfur (S).

The temperature of the molten iron and the liquid slag, as they are taken out of the blast-furnace, is approximately 1500 ^{0}C. The rate and manner of cooling of the liquid slag into a solid form affects the structure and characteristics of the solid slag.

Depending on the rate and manner of cooling of the liquid blast-furnace slag three types of slag result in solid form. These are:

- Air cooled blast-furnace slags: They result from solidification of molten slag under atmospheric conditions; subsequent cooling may be accelerated by application of water to the solidified surface [22]. Because of the slow cooling process, crystalline forms of calcium silicates occur in the slag and this type of structure does not show hydraulic binding property. This gray and hard slag is used as an aggregate for concrete [7].

- Expanded blast-furnace slags: They are obtained by controlled processing of molten slag with water or water and other agents such as steam or compressed air, or both [22].This process results in a lightweight cellular material. They are used as lightweight aggregates for concrete [23-24].

- Granulated blast-furnace slags: They are defined as “the glassy, granular material formed when molten blast-furnace slag is rapidly chilled, as by immersion in water” [6, 22, 25]. Rapid “quenching” or chilling minimizes the crystallization and converts the molten slag into fine aggregate-sized particles, composed of predominantly noncrystalline material. In the past, granulated blast-furnace slag was often obtained by simple immersion of the molten slag in water. More efficient modern granulation systems use high-pressure water jets [26]. Another process of rapid cooling sometimes referred to is slag pelletization [27]. In this process the molten slag passes over a vibrating feed plate, where it is expanded and cooled by water sprays; it then passes into a rotating drum which throws it into the air where it rapidly solidifies into spherical pellets of high glass content [27-28].

Among the various types of blast-furnace slags, the granulated blast-furnace slag is the only product suitable for use as a cementitious ingredient when it is in a finely divided (ground) form. This is due to the presence of high contents of silica (30%-40%) and alumina (7%-20%) in noncrystalline state. Ground granulated blast-furnace slags show pozzolanic reactions similar to those of finely divided natural pozzolans and fly ashes. In other words, when they are in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties. Since these slags contain a relatively high content of calcium oxide (30%-40%), they also show self-cementitious properties to a certain extent.

Ground granulated blast-furnace slags are used as cementitious ingredients in mortars also containing some limes, as additions in producing blended cements or as admixtures in concretes [7].

2.4.1 Chemical Composition of Granulated Blast-Furnace Slags

Blast-furnace slags are all broadly similar in composition. Table 2.4 shows the range of chemical composition of blast-furnace slags produced in some countries [29, 30, 31].

As can be seen from the table, the amount of SiO_2, Al_2O_3 and CaO in most blast furnace slags varies from 30 to 40%, 7 to 19% and 30 to 50%, respectively. Iron oxide, magnesia, manganese oxide, and sulfur are other ingredients in minor quantities [1].

Table 2.4 Chemical Composition of Blast-Furnace Slags, %

Chemical Properties	US and Canada*	South Africa	Australia	Turkey
CaO	29 - 50	30 - 40	39 - 44	34 - 41
SiO_2	30 - 40	30 - 36	33 - 37	34 - 36
Al_2O_3	7 - 18	9 - 16	15 - 18	13 - 19
Fe_2O_3	0.1 - 1.5	-	0 - 0.7	0.3 - 2.5
MgO	0 - 19	8 - 21	1 - 3	3.5 - 7
MnO	0.2 - 1.5	-	0.3 - 1.5	1 - 2.5
S	0 - 2.0	1.0 - 1.6	0.6 - 0.8	1 - 2

*upper and lower limits are taken from references 29, 30, 31.

2.4.2 Factors Determining Cementitious Properties of Ground Granulated Blast-Furnace Slags

The main factors that determine the cementitious properties of ground granulated blast-furnace slag are [7]:

- Chemical composition of the slag
- Alkali concentration of the reaction system

- Glass content (amorphousness) of the slag
- Fineness of the slag, and
- Temperature during the early phase of the hydration process

The interrelation of all the above factors is very complex.

In general, the cementitious properties of rapidly cooled blast-furnace slags are positively affected by an increase in certain chemical constituents such as lime and alumina, and are negatively affected by an increase in silica. Therefore, earlier attempts to relate the cementing quality of ground granulated blast-furnace slag depended on simplified chemical moduli (basicity ratio) such as shown below [7].

$(CaO + MgO + Al_2O_3)/SiO_2 \geq 1$

Recently, the evaluation of the cementing properties of ground granulated blast-furnace slag has been considered to be inadequate as an evaluation criterion for practice. At present, determination of slag activity index for ground granulated blast-furnace slag is the basic criterion for finding the relative cementitious potential of this material. This method is recommended by ASTM C 989 [32].

CHAPTER 3

A GENERAL LITERATURE SURVEY ON IMPROVING STRENGTH AND WATER RESISTANCE OF GYPSUM

In this study, it is aimed to improve the strength and water resistance of gypsum pastes with elevated temperature effect by using pozzolanic material incorporation to gypsum. Therefore, in this chapter, a general literature review of studies on improving strength and water resistance of gypsum is presented.

3.1 Studies on Improving the Water Resistance and Strength of Gypsum by Using Polymeric Substances and/or Fibers

Water related deterioration is the principal source of difficulty with calcium sulfate based materials. For this reason, gypsum products are generally used in the building industry as a surface finish on interior walls and in the production of drywall products for interior lining and partitioning where structural requirements are low. Therefore, to enhance water resistance and strength of gypsum has prime importance to be able to also use gypsum in outdoor applications.

The two general methods used for providing water resistance to gypsum with water proofing admixtures are :

1. To prevent the migration of water by applying waterproofing materials on gypsum surface to form impervious coating.

   The technique used in this method includes protection of gypsum by applying water proofing materials on its surface. The method depends on the formation of a good bond between the gypsum and the protective material and is therefore prone to adhesion failure because of the critical surface preparation requirements.

   Water proofing materials are applied on gypsum surface to form impervious coatings that prevent the passage of water in liquid form and may also retard vapor transmission in varying degrees, depending on the type of coating. Since the treatment prevents the ingress of water in liquid form, it also stops the transport of water soluble salts into the gypsum. Different types of polymers such as chlorosulfonated polyethylene, epoxy, methacrylates etc. are used for this purpose.

2. To include waterproofing admixture into gypsum during mixing of the materials.

   In this method, the ingress and migration of moisture in liquid and vapor can be prevented or retarded to varying degrees by the incorporation of a waterproofing admixture in gypsum mix.

   A waterproofing admixture is in a powder, liquid or suspension form. When mixed with fresh gypsum, the admixture imparts a water repelling or hydrophobic property to the hardened gypsum. The most widely used waterproofing admixtures for gypsum are metal stearates, siliconates, acrylics and methacrylates.

Earnshaw [33] studied polymer impregnation of cast gypsum to improve the strength of the porous solid. Test specimens were prepared from an industrial gypsum plaster and water, mixed in a water/powder ratio of 0.50. The slurry was vibrated into gang moulds to form circular cylinders 25 mm in diameter by 13 mm high, which were dried to constant weight at 40 ^{o}C. Control specimens were tested in this condition, while the remainders were impregnated with polymethyl methacrylate in the following manner. Specimens were immersed in methyl methacrylate monomer. When saturated (after 10 min) they were individually wrapped in tin foil, heated to 70 ^{o}C for 24 h, and then slowly cooled to room temperature. Tensile strength was determined by fracturing specimens in diametral compression. As a result, it was obtained that the tensile strength of polymer impregnated specimens (10 MPa) were nearly 2.5 times higher than that of control specimens (4 MPa). It was stated that polymer impregnation of these specimens of cast gypsum produced a considerable improvement in tensile strength.

Whittaker and Jacobsen [34] showed that polymer impregnation of cast gypsum had great effects on the strength of gypsum and also these effects changed with the water - gypsum ratio. They used specimens prepared using an industrial gypsum plaster in various water - gypsum ratios and in various gang moulds. For compressive strength tests, circular cylinders 25 mm in diameter by 45 mm high and for tensile strength tests, cubes in dimensions of 25 mm x 25 mm x 25 mm were used. The water/gypsum ratio changed from 0.50 to 0.80. After casting, the samples were removed and dried at 100 ^{o}C for 24h and were stored in a vacuum dessicator at room temperature prior to testing. The cast materials were immersed for approximately 1.5 h in a solution made up of methyl methacrylate (100 parts), lauroyl peroxide (4 parts) and N-dimethyl-p-toluidine (2 parts, wt/wt). When the temperature of the soak solution had risen to 60 ^{o}C (about 90 min) the specimens were removed and allowed to stand at room temperatures for 30 min before testing. Compressive and tensile strength tests were determined. The results showed that with the increase in water/gypsum ratio from 0.50 to 0.80, for compressive strength tests; the strength of impregnated specimens changed 2.4 times to 6.6 times of that of control specimen and for tensile strength tests; the strength of impregnated specimens changed 5 times to 10 times of that of control specimen. As a result, it was pointed out that the enhancement in strength of gypsum due to polymer impregnation and also the effects of varying the water - gypsum ratio.

Çolak [35] used two methods to improve the strength and water resistance of gypsum. Firstly, the gypsum plaster was modified with acrylic latex. Secondly, epoxy - impregnated gypsum specimens, with a surface coating of epoxy, were tested after different periods of immersion in water at 20 ^{0}C. The effect of immersion in water on the porosity and the mechanical strengths of the composites were investigated. The specimens were prepared with the hydration of calcium sulfate hemihydrate, (β-hemihydrate). For the latex-modified gypsum, acrylic latex (methacrylic acid esters and styrene) was used. The latex/gypsum ratio was varied from 5% to 15% by weight of gypsum and water/gypsum ratio changed from 0.35 to 0.50 by weight. After the castings were made, they were cured in laboratory conditions at 20 ^{o}C and 65% relative humidity for 7 days followed by drying in an oven at 40 ^{o}C for 24 h. Porosities were measured by using water displacement method. Density was calculated from the mass and volume of the sample. Flexural strength was determined by using 4 x 4 x 16 cm specimens tested under three-point loading on a span on 10 cm. To determine compressive strength, 4 x 4 x 4 cm specimens were tested. For the epoxy - impregnated gypsum, the specimens were 20 mm diameter and

40 mm long gypsum cylinders. The water/gypsum ratio was varied between 50% and 100%. As soon as the gypsum specimens were set, they were stored in laboratory conditions for 24 h. Then, they were dried to constant weight at 40 ^{o}C followed by cooling to room temperature in a desiccator. The specimens were impregnated with epoxy for 30 and 60 min and then were polymerised at 20 ^{o}C for 7 days. After polymerisation, the epoxy - impregnated gypsum specimens were not cleaned and had a surface coating of epoxy with a thickness ranging from approximately 0.5 mm up to 1 mm. Splitting tensile test was applied to the specimens. It was concluded that porosity decreased from 31.3% to 19.4% and compressive strength increased 1.5 times from 16 MPa to 24 MPa by using 10% latex addition with a water/gypsum ratio of 35% compared to unmodified gypsum with a water/gypsum ratio of 50%. About 5% latex addition did not lead to increase in flexural strength compared to unmodified gypsum. However, increase in polymer content from 5% to 10% caused a significant improvements in flexural behavior. Decreasing the water content from 40% to 35% positively influenced the mechanical behaviour of latex-modified gypsum and led to 43% increase in flexural strength compared to unmodified gypsum with a water/gypsum ratio of 50%. Epoxy impregnation did not lead to a significant increase in splitting tensile strength. Seven days of immersion in 20 ^{0}C water caused a reduction of about 70% in the mechanical strengths of latex - modified gypsum, whereas epoxy - impregnated gypsum composites with a surface coating of epoxy retained 100% of their original strengths even after 7 days exposure to water.

Gypsum plaster, like other inorganic cements, is strong in compression but weak in tension. These brittle characteristics prevent the effective utilization of the high compressive strength in structural applications. A great improvement could be expected to result by incorporating fiber reinforcement in the gypsum plaster matrix and a composite of improved tensile strength can be obtained.

Bijen and Van der Plas [36] studied hybrid effects of polymers and fibers on the gypsum matrix. An investigation was performed on mechanical properties such as bending strength and tensile strength and also water absorption. The composite consisted of 54.5% of α-hemihydrate gypsum, 38.5% of polymer (thermosetting acrylic), 5.4% of melamine resin, 0.27% of a catalyst, 1.2% of an anti - foaming agent and 13% of glass fiber by weight of the matrix. The composites were cured for 1 to 7 days at 30 ^{o}C and 40% RH. Subsequently, they were stored at 20 ^{o}C and 65% RH. Four-point bending tests and tensile stress-strain tests were performed. While modulus of rupture of polymer modified glass fiber composite was 75 MPa, that of glass fiber reinforced plain gypsum was 26 MPa, similarly, tensile and bending strengths of former were 32 MPa and 9 MPa respectively but those of latter were 12 MPa and 6 MPa. The mass change due to water absorption when immersed in liquid water was 10% for 25 days and 16% for 150 days. The results showed that the polymer - modified glass fiber - reinforced gypsum had good mechanical properties under tension and, unlike unmodified gypsum. A variety of new outdoor applications were likely to be possible for this composite material.

3.2 Studies on Improving the Water Resistance and Strength of Gypsum by Incorporating Portland Cement and/or Pozzolans

As explained in previous section polymer modification and impregnation or especially glass fiber addition made it possible to produce gypsum products with improved water resistance and strength. However, the use of these processes in the production of gypsum products is limited by their very high cost. Therefore, water resistant gypsum binders suitable for plaster and masonry work have been developed by blending gypsum with portland cement and pozzolans. In literature, generally, the gypsum used with portland cement and/or artificial pozzolans is by-product gypsum.

Positive results have been obtained for the “gypsum + portland cement” blends containing fly ash [37] or granulated blast furnace slag [4] or natural pozzolans [3, 38].

Yan and You [37] developed a new binder with high strength and water resistance using fly ash and flourogypsum as main raw materials, as well as portland cement as stimulator. Flourogypsum, fly ash, and cement were blended in five different types by weight as can be seen in Table 3.1. The pastes were mixed by machine for 3 min, cast into 4 x 4 x 16 cm moulds for test of strength and then vibrated for 2 min. The samples were kept in air at 20 °C for 24 h. After demoulding, some samples were cured in air at 20 °C, and the rest were cured in water at 20 °C until the date of testing.

Table 3.1 Proportions (%) and Water/Binder Ratios of Binders [37]

Sample Types	Flourogypsum	Fly Ash	Portland Cement	Aluminate Cement	W/B
G1	36	64	-	-	0.22
G2	36	60	4	-	0.22
G3	35	57	8	-	0.22
G4	31	53	16	-	0.22
A4	31	53	-	16	0.20

Table 3.2 Strengths of Studied Binders (MPa) [37]

	Samples Cured in Air						Samples Cured in Water			
	Compressive Strength			Flexural Strength			Compressive Strength		Flexural Strength	
	3d	28d	91d	3d	28d	91d	28d	91d	28d	91d
G1	very low			very low						
G2	4.4	28.1		0.90	4.41					
G3	7.5	31.5		1.37	4.84					
G4	15.4	52.7	72.7	3.54	7.32	7.75	59.3	77.3	5.99	7.11
A4	14.8	40.8	44.3	3.05	4.28	4.56	38.9		4.24	

The strengths that they found are shown in Table 3.2. It was claimed that the plain mixture of flourogypsum and fly ash did not gain cementitious property and they cited portland cement had to be added to the mixture to excite its potential cementitious property. As can be seen from Table 3.2, the strengths of pastes in the early age were not high, but accompanying the continuous development of hydration, the strengths increased continuously. When the proportion of cement that was both stimulator and hydraulic component in the binder increased from 8% in G3 to 16% in G4, the properties of the binders were improved greatly. G4 had satisfactory early strength and very high later strength. They showed that G4 eliminated the shortcoming of normal gypsum plaster that lost its strength in humid environment due to its low water resistance. G4 gained even higher compressive strength because the pozzolanic reaction of fly ash proceeded more fully and more tobermorite gels yielded in the paste cured in water than in air.

Singh and Garg [4] proposed a water resistant gypsum binder to be produced by blending the ground granulated slag, portland cement and an organic retarder with calcined phosphogypsum (β-hemihydrate) followed by grinding together in a ball mill to obtain a uniform product. The chemical composition of blended gypsum binder they used is given in Table 3.3. The porosity and water absorption of the structure was investigated and a relationship with mechanical properties was established.

Table 3.3 Chemical Composition of Blended Gypsum Binder [4]

Chemical Properties	%
CaO	37.30
SO_3	39.65
SiO_2	8.20
$Fe_2O_3 + Al_2O_3$	9.00
MgO	1.80
Loss on Ignition	4.10

The physical properties of the binder tested according to the Indian Standard, IS: 4031 – 1968 (methods of physical testing for hydraulic cements). The physical properties of the binder can be seen in Table 3.4. It could be seen from Table 3.4, the compressive strength of blended gypsum binder increased with time. The authors explained the reason of the gain in strength of the blended gypsum binder that this was due to the formation of ettringite and tobermorite gels in the gypsum matrix as hydraulic products.

Table 3.4 Physical Properties of Water Resistant Gypsum Binder [4]

Properties	Blended Gypsum Binder	Plain Gypsum Plaster
Fineness, cm^2/g	3100	3000
Setting time, min		
Initial	70	25
Final	145	-
Bulk density, g/cm^3		
1-day	1.54	1.10
3-day	1.68	-
7-day	1.85	-
28-day	1.95	-
Compressive Strength, MPa		
1-day	10.10	13.30
3-day	23.10	-
7-day	28.60	-
28-day	35.00	-
Water absorption, %	6.0	33.0

The performance of blended gypsum binder was studied by immersing the 28 days hardened 2.5 cm cubes of the binder in water as shown in Table 3.5. It was evident from the table that with the increase in immersion period, the water absorption of blended gypsum binder increased without leaching of the matrix whereas plain phosphogypsum plaster exhibited leaching after 3 days of immersion. The authors explained the reason of this behavior that this superior behavior of blended gypsum binder towards water could be ascribed to the filling of voids and pores of the gypsum matrix with ettringite and tobermorite gels obtained as a hydration products.

Table 3.5 Performance of Blended Gypsum Binder in Water [4]

Immersion Period (hr)	Water Absorption (%)	
	Blended Gypsum Binder	Phosphogypsum Plaster
2.0	1.86	27.94
8.0	2.09	30.73
24.0	2.89	32.09
72.0	3.77	34.31
168.0	3.91	leaching
672.0	5.53	leaching

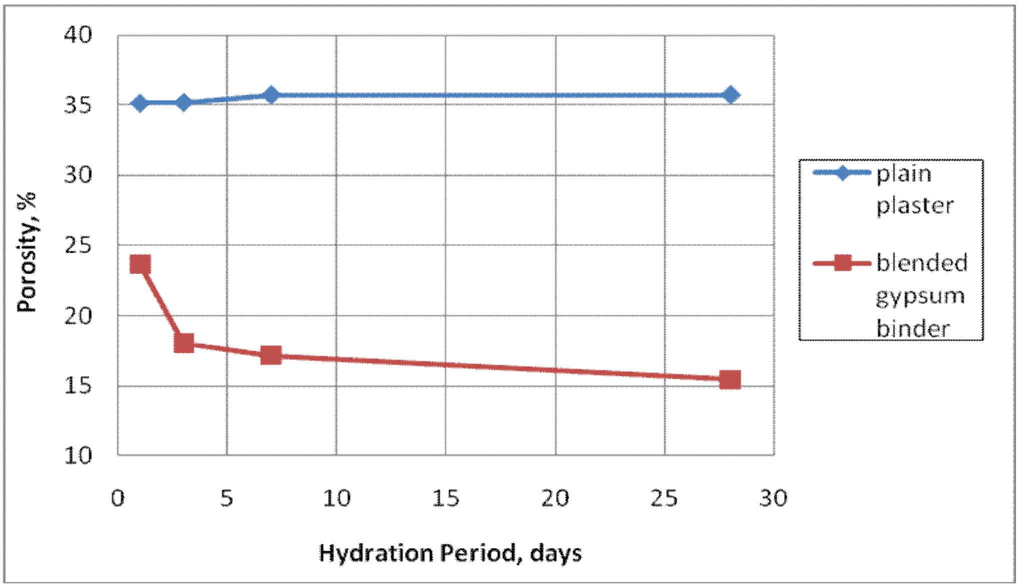

Figure 3.1 Change in Porosity with Hydration Period of Blended Gypsum Binder and Plain Plaster [4]

The effect of hydration period on gypsum plasters that Singh and Garg [4] tested was shown in Figure 3.1. It can be seen from Figure 3.1, the total porosity decreased with increase in the hydration period of blended gypsum binder. The rate of decrease of porosity was greater at early stages of hydration but became approximately linear after 7-days of hydration. It was explained by authors that these data clearly exhibited that reduction in porosity with curing period may be the reason behind the strength characteristics and durability performance of blended gypsum binder. Figure 3.2 showed the relationship, between compressive strength and porosity of blended gypsum binder with different hydration periods and of plain plaster. It can be seen that this relationship was different from each other and follow different lines with hydration periods. As the porosity increased, the compressive strength of the binder decreased. It also demonstrated the strength values of blended gypsum binder increased with the increase in curing period.

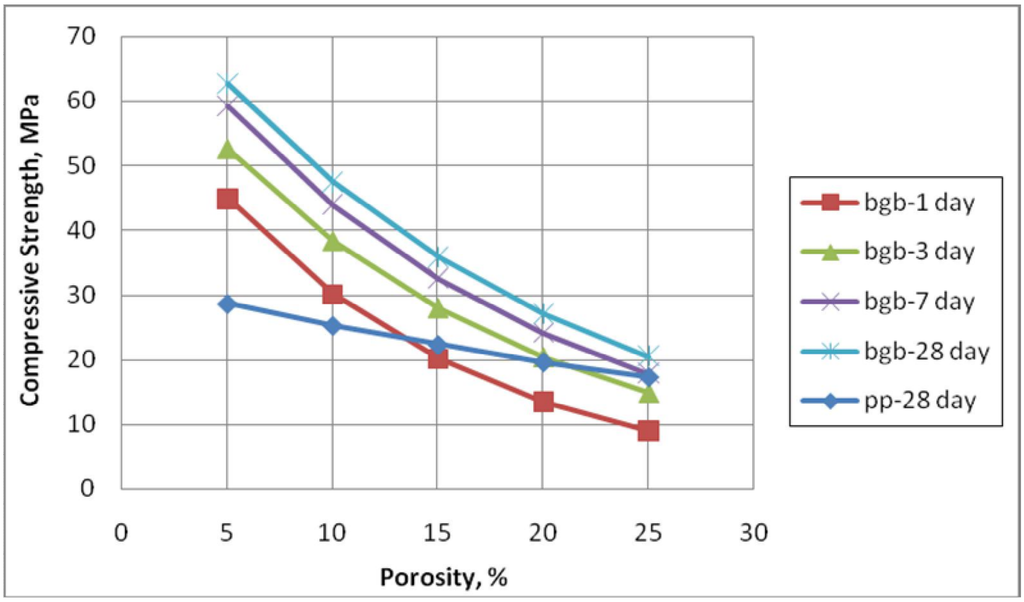

Figure 3.2 Relationship Between Compressive Strength and Porosity of Blended Gypsum Binder (bgb) and Plain Plaster (pp) [4]

As a conclusion, the authors determined that the porosity of the blended gypsum binder were lower than those of the plain plaster, the major parameter determining the development of strength, structure and durability of blended gypsum binder was porosity and enhancement in compressive strength of gypsum binder with hydration period could be correlated with the reduction in porosity of the blended gypsum binder matrix.

Çolak [38] dealt with the effect of gypsum – portland cement and gypsum – portland cement – natural pozzolan ratios on the physical, mechanical, and durability properties of "gypsum + portland cement + natural pozzolan" blends. In this study, a water - resistant gypsum binder was tried to produce by blending natural pozzolan and ordinary portland cement with calcium sulphate hemihydrate (β-hemihydrate). To effectively counteract the loss of workability and rapid setting caused by high gypsum content, a naphtaline - based superplasticizer was incorporated into the mixtures. The water - binder ratio was 0.50 by weight, except in the mixtures containing superplasticizer where the water - binder ratio ranges from 0.40 to 0.45. Each mix was designated by the mixing proportions of the materials. For example, 41 : 41 : 18 identified a mix with a composition of 41% gypsum, 41% portland cement, and 18% natural pozzolan. Similarly, 41 : 41 : 18S1 represented the same mix containing a superplasticizer at a dosage of 1% by weight of binder. In the "gypsum + portland cement" blends, the gypsum was replaced by cement in the proportions 20%, 30%, 40%, and 50%, respectively. The "portland cement + natural pozzolan" blends were made with ordinary portland cement with 20%, 30%, and 40% natural pozzolan replacements. The pastes were mixed by hand for 1 minute, cast into 4 × 4 × 4 cm moulds for compressive strength test or 4 × 4 × 16 cm moulds for physical tests and then compacted by jolting. The samples were stored in a fog room at 20°C and about 95% relative humidity for 1 hour. At the end of this period, they were demoulded and cured in the following regimes:

(a) water curing for 28 days at 20 ± 2°C

(b) fog curing for 28 days at 20 ± 2°C and 95% relative humidity

(c) fog curing for 28 days at 20 ± 2°C and 95% relative humidity,
followed by further curing in an oven at 40°C to a constant weight

These curing regimes were tested to see the effect of curing conditions on the mechanical behaviors of "gypsum + portland cement + natural pozzolan" blends. The specimens stated in the matter of (c) were used for the water absorption and porosity tests. These specimens were weighed, then immersed into water to measure their compressive strength after different periods. After 7 days, the absorbed volume of the liquid was determined by measuring the increase in weight. The porosity of samples was determined by the water-replacement method (Archimedes method), the weight of the dry and wet specimen and its weight in water were measured (apparent porosity). The author showed that porosity of blended gypsum binders ranged from 12% to 37%. The porosity of gypsum was found to be about 34%. The water absorption of blended was high, reaching 27% in the blends with a greater proportion of gypsum. The “gypsum + portland cement“ blends possessed good water resistance, which was further enhanced by the addition of natural pozzolan and superplasticizer. The water cured blends with the composition of 41 : 41 : 18 (gypsum : portland cement : natural pozzolan) and 41 : 41 : 18S1 (gypsum : portland cement : natural pozzolan : 1% superplasticizer) offered a compressive strength of approximately 20 MPa at room temperature. Their good resistance to water decreased as the gypsum content in the mixture was raised.

Murat and Attari [3] studied on modification of some physical properties of gypsum plaster by addition of clay minerals. Different clay minerals (montmorillonite, muscovite, sepiolite, attapulgite, talc, kaolinite and metakaolinite), added to gypsum plaster powder before gauging, modify some physical properties of the binder after hardening, e.g. compressive and flexural strengths, total open porosity and pore size distribution. The mineral binder used for investigations is a gypsum plaster, at 95 % β-hemihydrate, produced by Lafarge. Different clay minerals (clay fraction generally higher than 90%) such as Ca and Na montmorillonite, muscovite (mica), talc, sepiolite, attapulgite, kaolinite and metakaolinite were added to gypsum plaster powder before gauging (clay mineral weight fraction up to 20%). Metakaolinite was obtained by thermal activation (calcining in a fixed-bed reactor at 750 °C for 5 hours) of a poorly - crystallized kaolinite clay (sample at 95% in kaolinite). The sample was added alone or after mixing with a chemical activator, e.g. solid calcium hydroxide (CH) or ordinary portland cement (PC). Complementary investigations were made on gypsum plaster added with silica (sand at 95% quartz). Preparation of samples was made by dry mixing gypsum plaster + the mineral additive (silica or clay mineral), then addition of the mix to water, gauging at normal consistency and pouring the paste into plexiglass molds of different forms and sizes: miniprisms (2 x 2 x 8 cm) for flexural tests, minicylinders (diameter 2 cm and height 4 cm) for compressive tests. All samples where cured at 20 ^{o}C either under relative humidity (90 ± 5%) or under liquid water, and dried at 50 ^{o}C up to constant weight before test. As a result of the tests, it was found that strength of all samples with content of clay mineral higher than 10% (weight fraction) was sensitively lower than strength of pure gypsum plaster. Several strength values for samples with 5% or 10% of clay addition, and cured in different conditions and different times, may be higher or equal to strength of the pure gypsum plaster paste. Many other ones were lower: for example, with samples containing metakaolinite + calcium hydroxide or portland cement, only addition of portland cement led to a good level of compressive strength, as compared with strength of pure gypsum plaster. Addition of metakaolinite + calcium hydroxide did not bring any strength improvement of the material. These results could lead to define the composition of samples for other investigations on physical properties: choice of 10% as weight fraction of clay mineral added to gypsum plaster powder before gauging, and 6% and 10% of metakaolinite for sample added with metakaolinite + calcium hydroxide or metakaolinite + portland cement, with MK/CH (Metakaolin/Calcium Hydroxide)=3 and MK/PC (Metakaolin/Portland Cement)=1 (in weight), respectively. On the other hand, the porosity of the pure gypsum was 40.35% and the porosity of the binders changed from 39.89% to 48.90%. Measurements on gypsum plaster containing 10% of clay mineral and hydrated at 7 days showed that whatever was the additive, the total open porosity remained in the range of macroporosity . However, some percentage of mesoporosity (pore with radius r <100 nm) appeared for addition of metakaolinite + calcium hydroxide or portland cement.

CHAPTER 4

EXPERIMENTAL STUDY

4.1 Experimental Program

The experimental program of this study consisted of five main parts:

a) Determination of the chemical and physical properties of the materials used according to the related ASTM standards.

b) Proportioning of 13 different types of gypsum mixtures containing various percentages of fly ash and blast-furnace slag.

c) Obtaining pastes from 13 different mixtures, and casting 5-cm cube specimens from them.

d) Applying different curing regimes to the cube specimens made with different percentages of fly ash or blast-furnace slag, and testing them at various ages such as 7, 14, and 28 days.

e) Analyzing the microstructure of the pastes by X-Ray Diffraction (XRD) method.

4.2 Materials

4.2.1 Gypsum

Gypsum rock from which the gypsum to be used in this investigation was purchased from Sargın Gypsum Factory in Şereflikoçhisar - Ankara, Turkey. The following operations were conducted for finding the suitability of this gypsum rock for gypsum production, and for producing the gypsum in the Materials of Construction Laboratory of Middle East Technical University:

1. Determination of the chemical composition and suitability of the raw material for gypsum production.
2. Calcination.

Determination of the Chemical Composition -- The sample of gypsum rock was ground to pass a 250-µm (No.60) sieve, as required by ASTM C471 [39]. (TS 370 [40] requires that the amount of material retained on 0.2 mm sieve should not be more than 35%. The sample obtained was in conformance with that specification as well). The chemical composition of the sample was determined by X-Ray Fluorescence (XRF) method. The results are shown in Table 4.1.

ASTM C22 – Standard Specification for Gypsum requires that the gypsum rock suitable for gypsum production should have at least 70% (by weight) of $CaSO_4.2H_2O$ in it.

As can be seen from Table 4.1, the CaO, SO_3 and H_2O contents of the gypsum rock intended to be used in the investigation were 32.15%, 45.35% and 20.75%, respectively. In other words, the $CaSO_4.2H_2O$ content of the gypsum rock was 98.25%. Thus, it conformed to the standard specification stated in ASTM C 22.

Calcination -- The hemihydrate gypsum (which is called "normal gypsum" in TS 370 [40]) to be used in this investigation was produced in the Materials of Construction Laboratory of Middle East Technical University by calcining the pulverized raw material in a 300 ^{0}C-capacity oven.

Table 4.1 Chemical Composition of the Gypsum

Chemical Properties	%
CaO	32.15
SO_3	45.35
SiO_2	0.10
Fe_2O_3	0.05
Al_2O_3	0.02
MgO	0.03
Loss on Ignition (H_2O)	20.75

In literature, the calcination temperature for obtaining hemihydrate gypsum is given as 100 to 190 ^{0}C, and usually between 140 ^{0}C and 190 ^{0}C. Therefore, a calcination temperature of 165 ^{0}C (an average temperature between 140 and 190 ^{0}C) was decided to be used. The following procedure was applied for the calcination process:

First the time for obtaining an anhydrite gypsum at 190 ^{0}C was investigated. This duration during which the gypsum achieved a constant weight was found to be 5 hours. Then the raw material was calcined for five hours and its water content was calculated. The hemihydrate gypsum thus obtained was found out to contain 0.58 molecules of water. In other words, the hemihydrate gypsum used in this investigation had a composition as $CaSO_4 \cdot 0.58H_2O$.

4.2.2 Pozzolanic Materials

Fly ash and ground granulated blast-furnace slag were two types of pozzolanic materials incorporated in the gypsum mixtures used in this investigation.

Fly ash -- The fly ash used in preparing some of the mixture types was obtained from Tunçbilek Thermal Power Plant in Kütahya, Turkey. Its chemical composition (as obtained by X-Ray Fluorescence (XRF) method) and physical properties are shown in Tables 4.2 and 4.3, respectively.

As can be seen from Table 4.2, "SiO_2+ Al_2O_3+ Fe_2O_3" content of this fly ash was 85.49%; thus it was an F-type fly ash according to ASTM C 618 since its "SiO_2+ Al_2O_3+ Fe_2O_3" content was higher than 70%.

Ground Granulated Blast-Furnace Slag -- The granulated blast-furnace slag used in this investigation was obtained from Ereğli Iron & Steel Factory, in Zonguldak, Turkey and ground in the Materials of Construction Laboratory of Middle East Technical University.

Table 4.2 Chemical Composition of the Fly Ash

Chemical Properties	%
CaO	2.38
SO_3	0.81
SiO_2	56.70
Fe_2O_3	11.23
Al_2O_3	17.56
MgO	2.38
Loss on Ignition (C)	3.27

Table 4.3 Physical Properties of the Fly Ash

Physical Properties	
Specific Gravity	2.22
Fineness	
Passing 45 µm, %	84
Blaine Fineness, m^2/kg	330
28-day Pozzolanic Activity Index, %	87.50

Table 4.4 Chemical Composition of the Blast-Furnace Slag

Chemical Properties	%
CaO	37.80
SO_3	0.70
SiO_2	35.10
Fe_2O_3	0.54
Al_2O_3	17.54
MgO	5.50

Table 4.5 Physical Properties of the Blast-Furnace Slag

Physical Properties	
Specific Gravity	2.90
Fineness	
Passing 45 µm, %	82
Blaine Fineness, m^2/kg	348

The chemical composition which was obtained by X-Ray Fluorescence (XRF) and physical properties are shown in Table 4.4 and 4.5, respectively.

4.2.3 Hydrated Lime

Hydrated lime was used in all mixtures containing pozzolans in this investigation in order to stimulate pozzolanic activation of the pozzolans.

The calcium hydroxide ($Ca(OH)_2$) content of the hydrated lime used in this study was found to be 90% by weight of ignited sample as a result of thermo-gravimetric analysis.

4.3 Proportioning of the Various Types of Mixtures for Use in This Investigation

The mixtures were produced using materials which were mentioned in the previous section. The types of mixtures and the percentages (by weight) of gypsum, pozzolans (fly ash or ground granulated blast furnace slag) and hydrated lime in them are given in Table 4.6.

For these mixtures, G, F and S represent gypsum, fly ash and slag, respectively, in Table 4.6. As can be seen from Table 4.6, the type of mixtures were categorized as “gypsum”, “fly ash + hydrated lime”, “slag + hydrated lime”, “gypsum + fly ash + hydrated lime” and “gypsum + slag + hydrated lime”.

In all types of mixtures containing pozzolans, hydrated lime was used at amount of 0.40 weight percent of the pozzolan. The amount of hydrated lime was decided by a small study on a comparison of compressive strengths of the mixtures having pozzolans and hydrated lime with different ratios, under the same curing conditions and at different ages.

Table 4.6 Types of the Mixtures and Materials in Them

Sample Types	Gypsum (%)	Fly Ash (%)	GGBFS* (%)	Hydrated Lime (%)
G	100	-	-	-
F	-	71.43	-	28.57
S	-	-	71.43	28.57
GF15**	80.19	14.15	-	5.66
GF30	62.50	26.79	-	10.71
GF45	46.61	38.14	-	15.25
GF60	32.26	48.39	-	19.35
GF75	19.23	57.69	-	23.08
GS15	80.19	-	14.15	5.66
GS30	62.50	-	26.79	10.71
GS45	46.61	-	38.14	15.25
GS60	32.26	-	48.39	19.35
GS75	19.23	-	57.69	23.08

*GGBFS: Ground Granulated Blast Furnace Slag

** GF15, containing 15% pozzolanic material by weight actually consisted of 85 units gypsum, 15 units pozzolanic material, and 15*0.4 = 6 units lime. By considering the total weight of the mix as 100 units, the mix actually contains 80.19% gypsum, 14.15% pozzolanic material and 5.66% lime by weight.

4.4 Preparation of the Pastes from Each Mixture Type and Casting Operation

The amount of water to be used for the formation of gypsum pastes or mortars is an important factor affecting the porosity and strength of the product in hardened state. When a very high amount of water/binder ratio is used, there will be too much excess water left in the paste after the formation chemical reaction ($CaSO_4.2H_2O$), and upon evaporation of this excess water, there will be a lot of voids left behind which will lead to low strength. On the other hand, if a very small amount of "water/binder" is used, the paste will not be plastic enough to be shaped. In literature a water/binder ratio of 0.6 (by weight) is recommended as the lowest ratio at which the material is plastic enough to be shaped. Therefore, the "water/binder" ratio used in preparing the pastes from different mixtures of this study was decided as 0.6.

Once the amount of binding materials and water were decided, pastes were prepared by mixing each binding material with the appropriate amount of water. Each paste was mixed manually for about 60-70 seconds. Since there is no standard for an appropriate mixing time, this length of mixing time was decided to be sufficient for a thorough mixing, considering the fast-setting property of gypsums.

After the preparation of each paste, these pastes were cast into 5 x 5 x 5 cm molds. In the casting operation, the following procedure was applied: The paste was placed in the mold in three layers and each layer was consolidated by applying 10 strokes with a tamping rod. After the consolidation of the top layer, the surface of the paste was smoothened with a trowel.

The total number of 5 x 5 x 5 cm specimens cast for each type of mixture used in this investigation was 1122.

4.5 Curing Regimes Applied to Various Specimens and Tests

After the pastes were cast, all samples were stored in a fog room at 20°C and 95% relative humidity for 24 hours. At the end of this period, they were demolded and subjected to various curing regimes.

The curing regimes that the samples were subjected to after the first 24 hours were grouped as water curing, and elevated temperature curing.

1. Water Curing:

   This type of curing was applied to some specimens by keeping them in water at 20 ± 2°C until their testing days.

2. Elevated Temperature Curing:

   This type of curing was applied in two steps:

   a. Subjecting the samples to elevated temperatures at 50°C or 80°C in an oven for various durations (such as 4, 12, 24 and 72 hours) and taking them out for the application of the second step of curing.

      To prevent the loss of water necessary for hydration all samples to be subjected to elevated temperature curing were wrapped with aluminum foil paper before being introduced into oven. The foil paper wrapping was removed after the samples were taken out of the oven.

      Curing temperature and duration that the samples were subjected to can be summarized as follows:

Temperature, °C	Duration, hours
50	4 12 24 72
80	4 12 24 72

b. The second step followed for the curing of specimens that were already subjected to elevated temperatures was to place them in water and to keep them at 20 ± 2°C condition until the time of testing.

Then the following tests were performed on the specimens to evaluate the performances of them:

- The compressive strengths of the 1053 specimens were determined in saturated and surface dry condition at 7, 14 and 28 days. While determining the compressive strength of the specimens, the procedure stated in ASTM C 109 [41] to evaluate the compressive strength of hydraulic cement mortars was followed. Three specimens were tested for each testing age.

- Water absorption capacity and porosity of the 23 different mixtures were also determined to able to evaluate the performances of the mixes by comparing with their compressive strength values. While determining the water absorption capacity of the mixtures, the procedure stated in ASTM C 127 [42] to measure density, relative density (specific gravity), and absorption of coarse aggregate was followed.

The porosity of the samples was determined by the water - displacement method (Archimedes method), the weight of the dry and wet specimen and its weight in water were measured (apparent porosity). Three specimens were tested for each mixture type separately. The following steps were followed:

1. First, the various specimens cured in different regimes were taken out of water at 7, 14 and 28 days. Then they were put into an oven at 40°C for nearly 24 hrs up to a constant weight and the weights of oven dry samples were determined separately.

2. After that, the specimens were immersed into water at 20°C for 24 hours and after 24 hours, specimens were taken out from water; and rolled in a large absorbent cloth until all the visible films of water on them were removed. They were wiped individually and their weights were determined separately in the saturated surface dry state.

3. Finally, the samples were immersed in water again and their weights in water determined separately.

The absorption capacity of the samples was determined using following formula:

$$\text{Absorption Capacity, \%} = \frac{B - A}{A} \times 100$$

The porosity of the samples was determined by the water - displacement method (Archimedes method) using following formula:

$$\text{Porosity, \%} = \frac{B - A}{B - C} \times 100$$

where:
A = Weight of oven dry samples, in air
B = Weight of saturated surface dry samples, in air,
C = Weight of saturated surface dry samples, in water,

In summary, the total number of specimens used for the study can be seen in Table 4.7. It can be determined by considering following items:

- 13 different types of mixtures with 3 specimens for each test
- Subjecting the specimens to 3 different curing temperatures (20^0C, 50^0C and 80^0C)
- Subjecting the specimens to elevated temperatures at 50°C or 80°C in an oven for various durations (such as 4, 12, 24 and 72 hours)
- 3 different ages for compressive strength tests i.e. 7-day, 14-day, and 28-day
- Additionally, 69 specimens cast for determining water absorption capacity

Table 4.7 Total Number of Specimens Used for the Study

Curing Temperature	Number of Types of Mixtures		The Days of Strength Tests (7-, 14-, and 28-day)		Duration in Oven (4, 12, 24, 72 hrs)		Number of Specimens
For 20^0C	13*3=39	*	3	*	—	=	117
For 50^0C	13*3=39	*	3	*	4	=	468
For 80^0C	13*3=39	*	3	*	4	=	468
						+	
							1053
Specimens cast to determine water absorption capacities			(23 * 3 = 69)				69
						+	
Total Number of Specimens							1122

4.6 XRD Analysis of the Samples

In order to examine crystalline hydration products qualitatively, to observe some possible similarities and differences in the samples and to investigate the reasons behind the behavior of the mixtures, XRD analyses were applied to some samples.

XRD examinations were carried out for 7 various types of samples cured for 72 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C for 28 days. These were G, F, S, GF45, GS45, GF60 and GS60 types of samples, as described in Table 4.6.

The samples were chosen from all type of mixtures categorized as “gypsum”, “fly ash + hydrated lime”, “slag + hydrated lime”, “gypsum + fly ash + hydrated lime” and “gypsum + slag + hydrated lime”. XRD patterns of the hardened pastes were obtained by using a Cu-α1 radiation/40 kV x-ray diffractometer between 2-theta angles of 0° and 60°.

CHAPTER 5

TEST RESULTS AND DISCUSSIONS

5.1 Evaluation of the Performances of the Mixtures Having the Same Pozzolanic Material and Subjected to the Same Curing Regimes

The mixtures which were cured under the same conditions and had the same pozzolanic material but in different ratios were grouped in order to be able to evaluate the variations in their performances according to the change of pozzolanic material amount in them and the effect of curing time on their performances. The test results of the mixtures changed in the ±10% range of the results which can be seen in table form in the Appendix A.

As can be seen in Figure 5.1, for mixtures having fly ash as a pozzolanic material and cured at 20 ^{0}C in water; they have the maximum compressive strength values for GF60 for all curing days. Although the strength values are close to each other for different curing days, with increase in age, it can be seen increases in strength values as an evidence of the hydration. It is clear that the strengths of all mixtures having fly ash, hydrated lime, and gypsum are higher than that of G which has only gypsum and also that of F which has only fly ash and hydrated lime (except for GF15 at 7 and 14 days). It can be said that the addition of fly ash and hydrated lime into gypsum changed the behavior of the mixture. The mixtures despite having gypsum as a major constituent increased their strength under water. Also, it can be stated that this can be a proof of the pozzolanic activation of the fly ash with hydrated lime and gypsum.

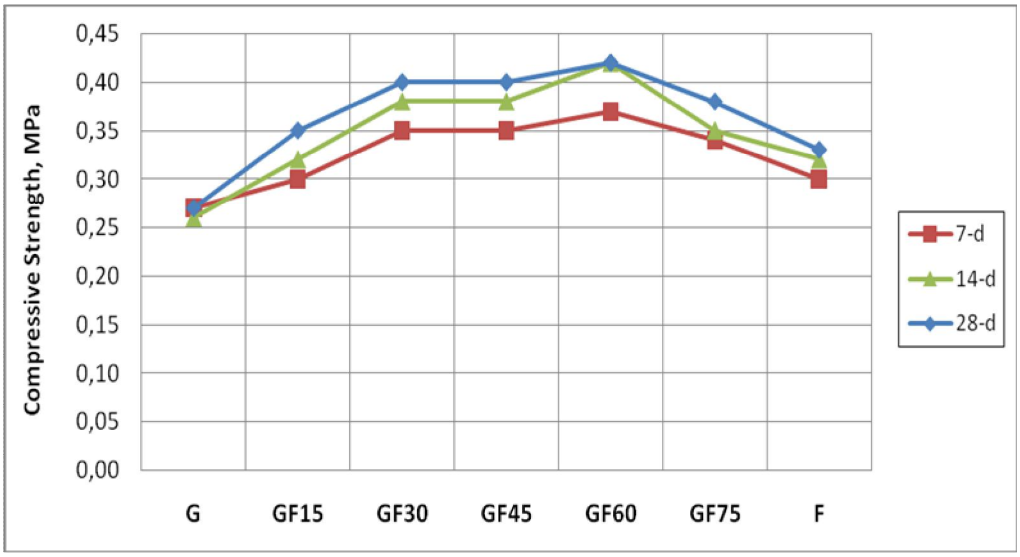

Figure 5.1 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured at 20 ^{0}C in Water at 7, 14 and 28 Days

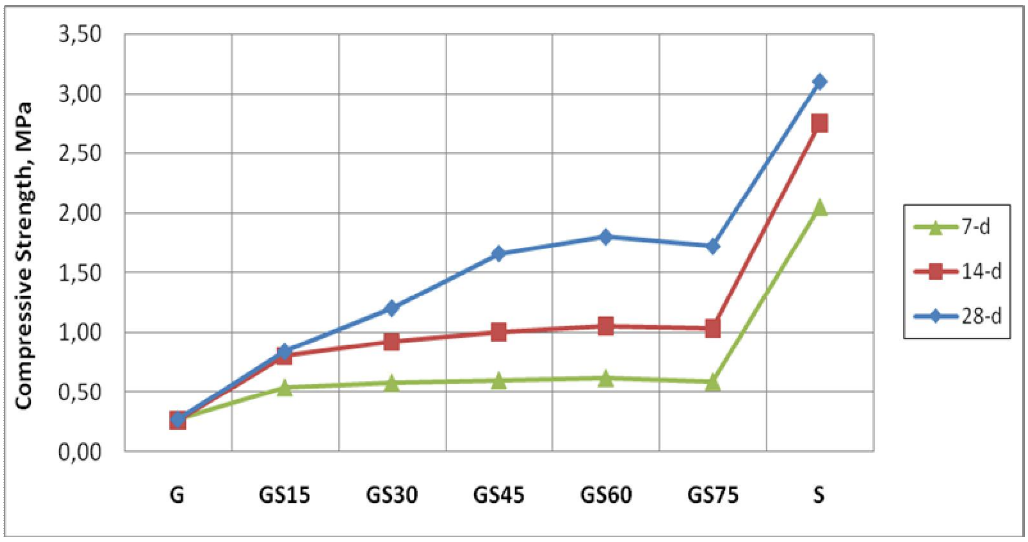

Figure 5.2 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured at 20 ^{0}C in Water at 7, 14 and 28 Days

On the other hand, as can be seen from Figure 5.2, for the mixtures having slag as a pozzolanic material and cured at 20 °C in water; the strength values of the mixtures having slag, hydrated lime and gypsum together are much higher than those of the mixtures having gypsum only. It can be said that addition of slag and hydrated lime into gypsum changed the behavior of the mixture. The mixtures despite having gypsum as a major constituent increased their strength under water. For mixtures containing slag, hydrated lime and gypsum; GS60 had the maximum compressive strength. Also, increases in strength values with the extension of curing time can be seen as an evidence of the hydration. On the other hand, it is obviously clear that the compressive strength of S which has only slag and hydrated lime is maximum for all curing times. The evidence of pozzolanic activation could not be seen for this time. Addition of gypsum into mixture containing slag and hydrated lime had a negative effect on the performance of the slag.

Figure 5.3 shows that for mixtures having fly ash as a pozzolanic material and cured for 4 hours in a 50 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.1 are valid. There is only one difference. The strength values of the mixtures having fly ash, hydrated lime and gypsum together are higher than that of F (having fly ash and hydrated lime only) except only for GF15 at 14 days; valid only for GF60 and GF75 at 28 days and for all mixtures at 7 days.

Similarly, as can be seen from Figure 5.4, for mixtures containing slag as a pozzolanic material and cured for 4 hours in a 50 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.2 are valid.

From Figure 5.5, it can be seen that for mixtures having fly ash as a pozzolanic material and cured for 4 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C;

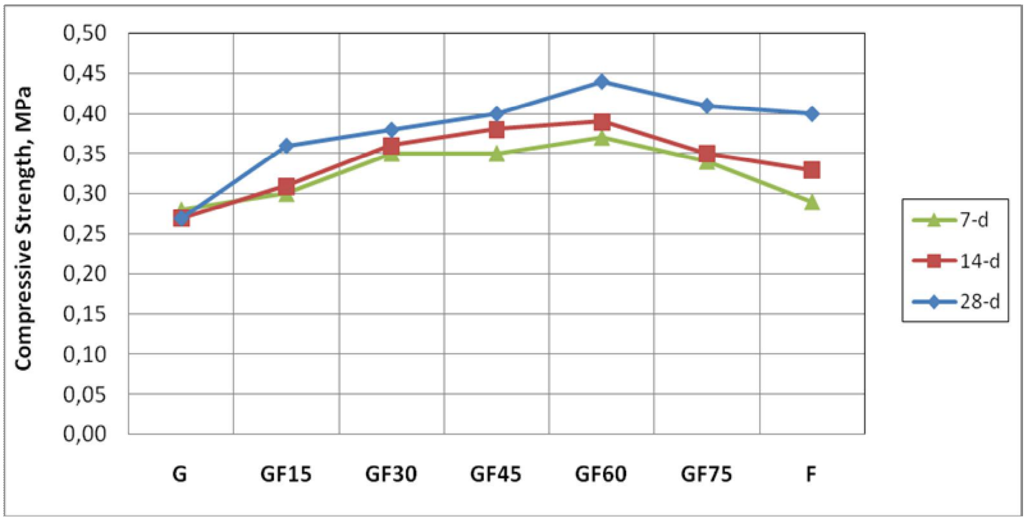

Figure 5.3 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

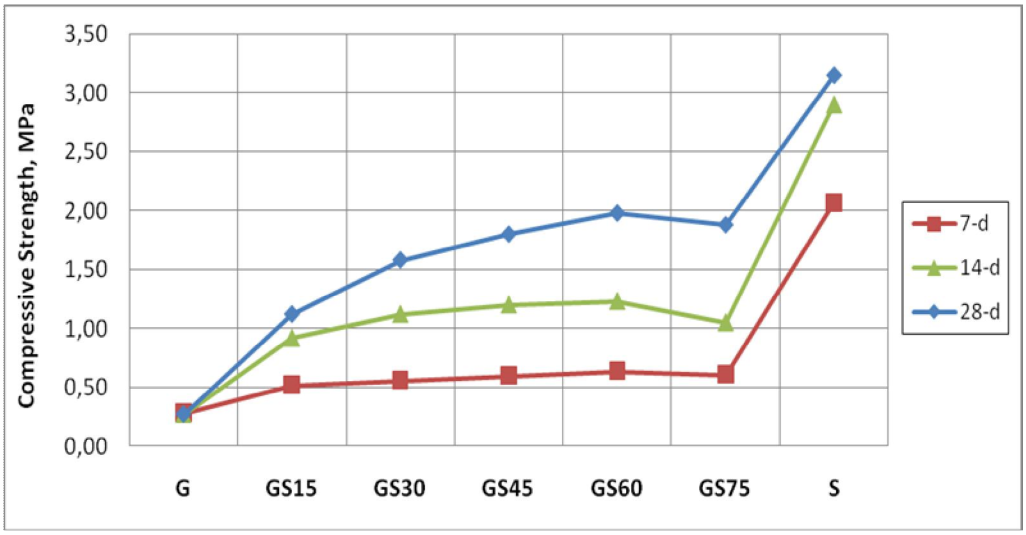

Figure 5.4 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

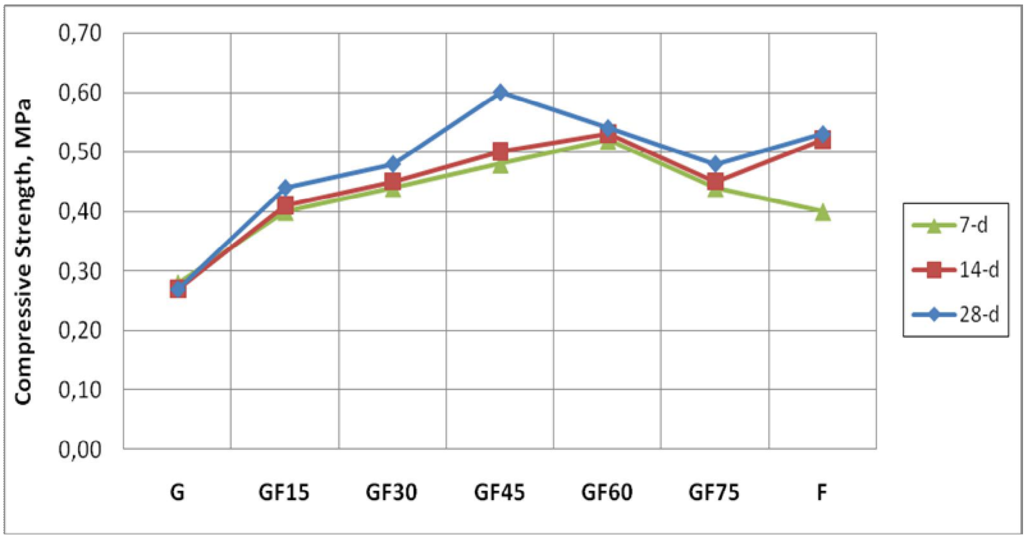

Figure 5.5 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

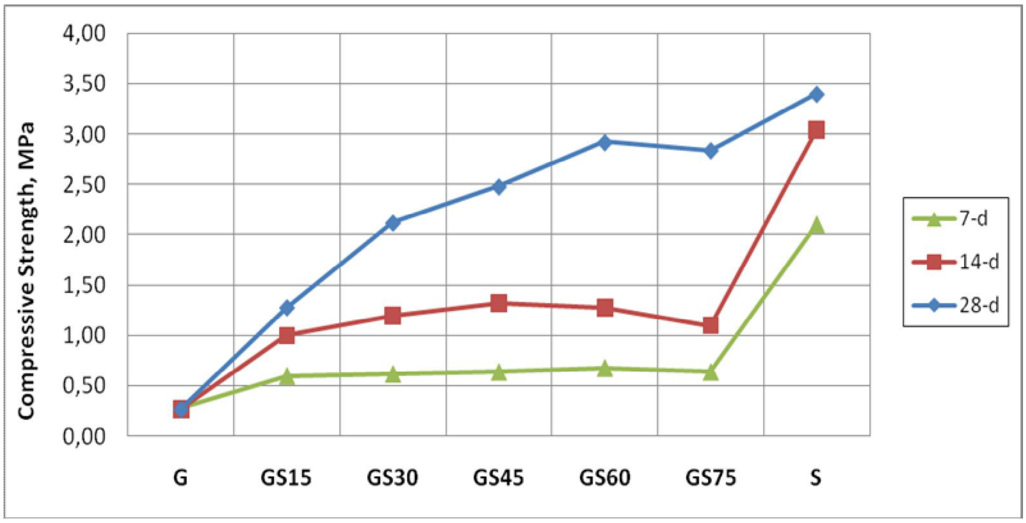

Figure 5.6 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C for 7, 14 and 28 Days

the explanations made for Figure 5.1 are valid. There are also a few differences. The compressive strength of GF60 is maximum at 7 and 14 days but GF45 has the maximum strength at 28 days. The strength values of the mixtures having fly ash, hydrated lime and gypsum together are higher than that of F (having fly ash and hydrated lime only) except for GF15 at 7 days; valid for GF60 at 14 days and for GF45, GF60 at 28 days.

Similarly, as can be seen from Figure 5.6, for mixtures containing slag as a pozzolanic material and cured for 4 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.2 are valid.

From Figure 5.7, it can be seen that for mixtures having fly ash as a pozzolanic material and cured for 12 hours in a 50 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.3 are valid.

As can be seen from Figure 5.8, for mixtures containing slag as a pozzolanic material and cured for 12 hours in a 50 ^{0}C oven, then cured in water at 20 ^{0}C; the compressive strength of S is maximum at 7 and 14 days but GS60 has the maximum strength at 28 days. Addition of gypsum into mixture containing slag and hydrated lime had a positive effect on the performance of the slag. There can be an evidence of pozzolanic activity at 28 days but this is not precisely obvious. The strength values of GS60 and S are close to each other. The other explanations made for Figure 5.2 are also valid.

From Figure 5.9, it can be seen that for mixtures having fly ash as a pozzolanic material and cured for 12 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.1 are valid. There are also a few differences. The compressive strength of GF60 is maximum at 7 and 14 days but GF75 has the maximum strength at 28 days.

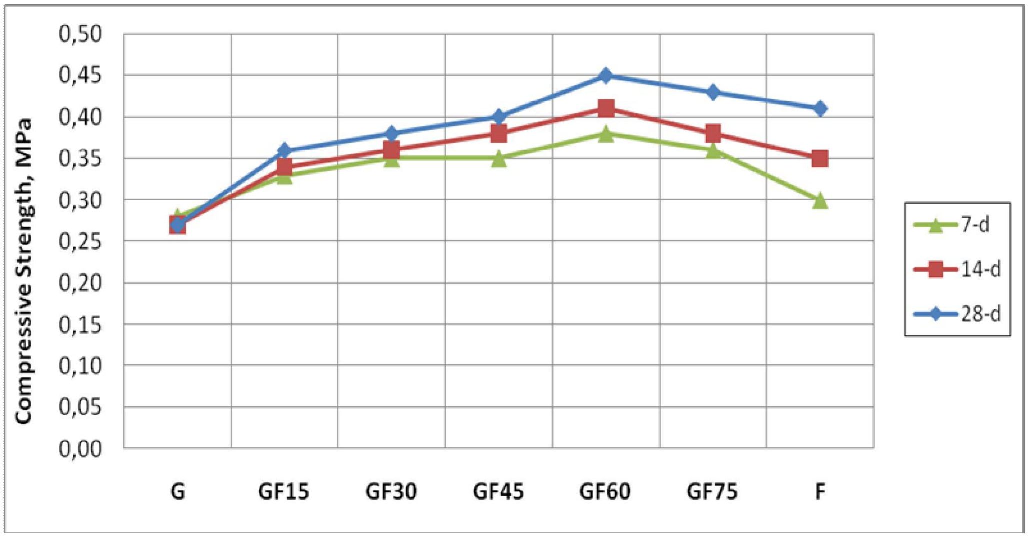

Figure 5.7 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured for 12 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

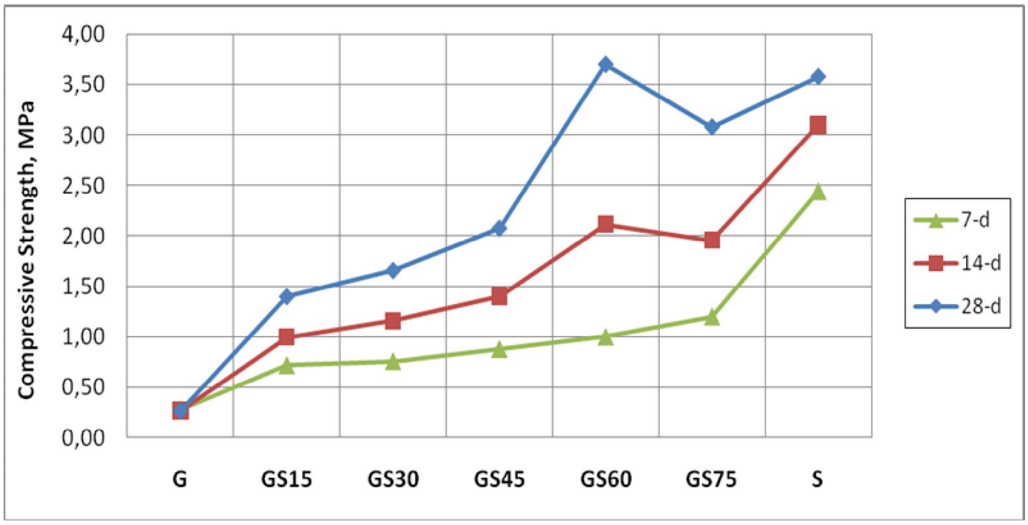

Figure 5.8 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured for 12 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

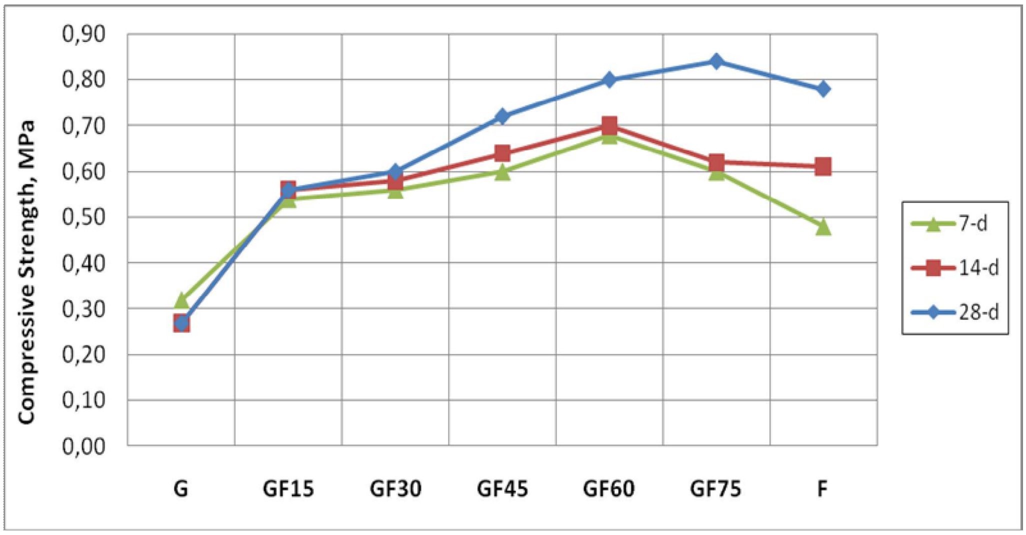

Figure 5.9 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured for 12 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

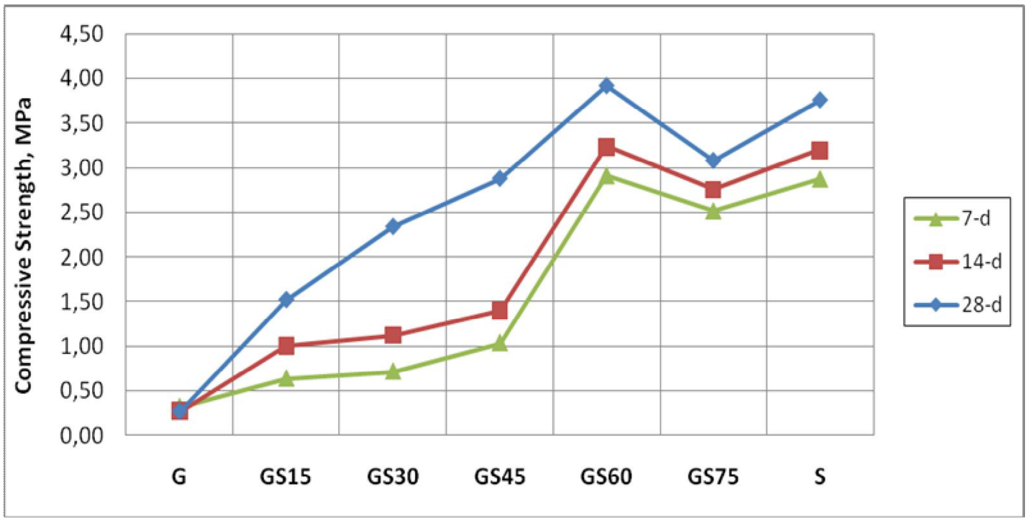

Figure 5.10 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured for 12 Hours in an 80 ^{0}C Oven Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

The strength values of the mixtures having fly ash, hydrated lime and gypsum together are higher than that of F except for GF15, GF30 at 14 days; valid for GF60, GF75 at 28 days and for all mixtures at 7 days.

As can be seen from Figure 5.10, for mixtures containing slag as a pozzolanic material and cured for 12 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C; the compressive strength of GS60 is maximum for all curing days. Addition of gypsum into mix containing slag and hydrated lime had a positive effect on the performance of the slag. There can be an evidence of pozzolanic activity but this is not precisely obvious. The strength values of GS60 and S are close to each other. The other explanations made for Figure 5.2 are also valid.

From Figure 5.11, it can be seen that for mixtures having fly ash as a pozzolanic material and cured for 24 hours in a 50 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.1 are valid. There are also a few differences. The compressive strength of GF60 is maximum at 7 and 14 days but GF75 has the maximum strength at 28 days. The strength values of the mixtures having fly ash, hydrated lime and gypsum together are higher than that of F except for GF15 and GF30 at 28 days; valid for all mixtures at 7 and 14 days.

As can be seen from Figure 5.12, for mixtures containing slag as a pozzolanic material and cured for 24 hours in a 50 ^{0}C oven, then cured in water at 20 ^{0}C; the compressive strength of GS60 is maximum at 28 days. Addition of gypsum into mixture containing slag and hydrated lime had a positive effect on the performance of the slag at 28 days. This can be a proof of the pozzolanic activation of the slag with hydrated lime and gypsum. The other explanations made for Figure 5.2 are also valid.

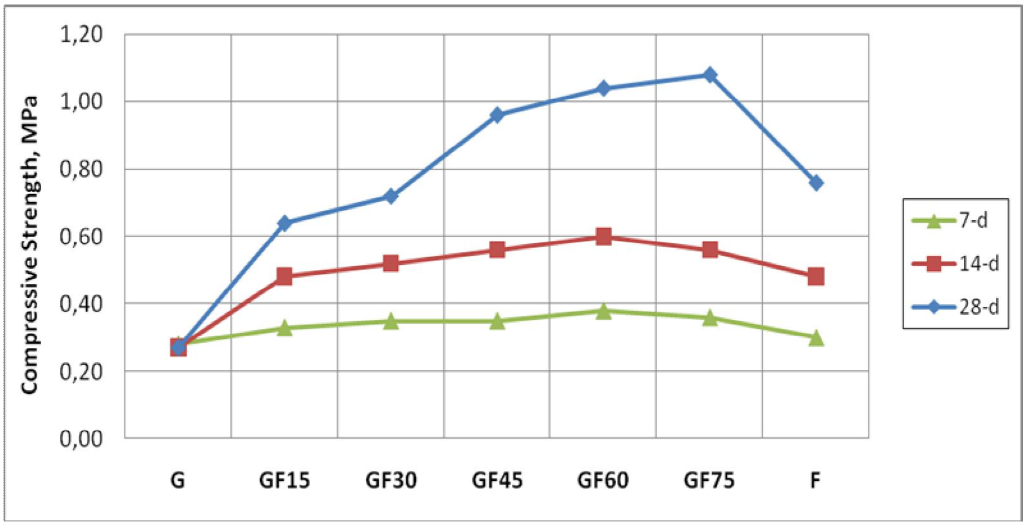

Figure 5.11 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

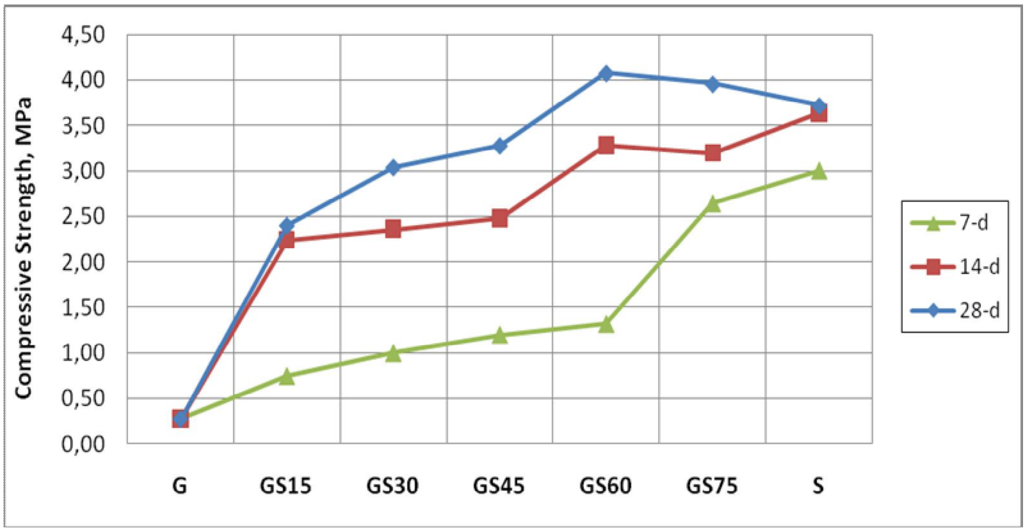

Figure 5.12 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

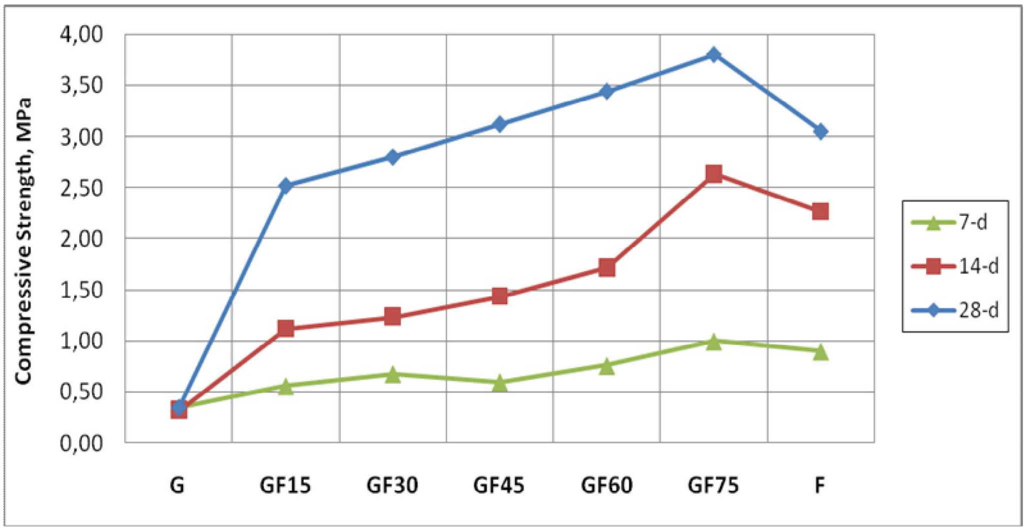

Figure 5.13 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

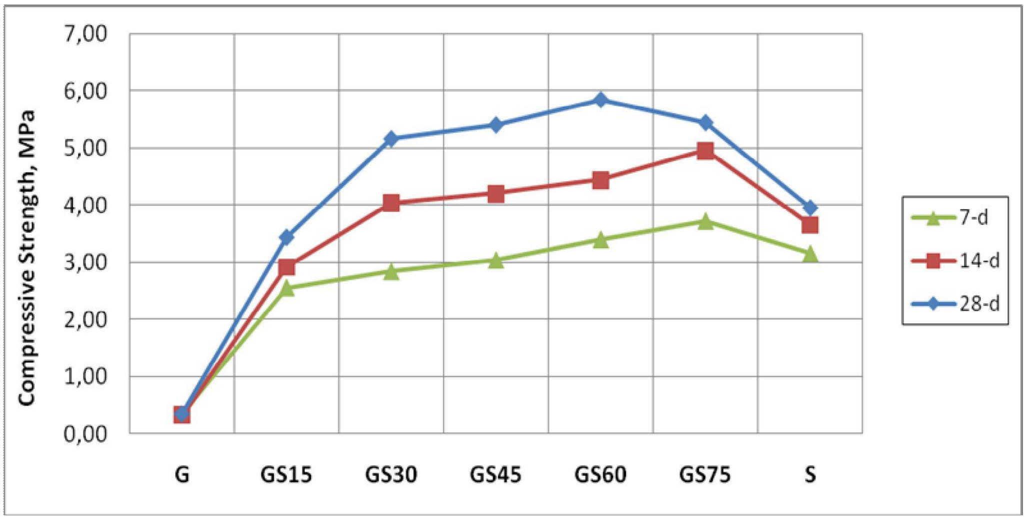

Figure 5.14 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

It can be seen from Figure 5.13, for mixtures having fly ash as a pozzolanic material and cured for 24 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.1 are valid. There are also a few differences. The compressive strength of GF75 is maximum for all curing days. The strength values of the mixtures having fly ash, hydrated lime and gypsum together are higher than that of F except for GF15 and GF30 at 28 days; valid for GF75 at 7 and 14 days.

From Figure 5.14, it can be said that for mixtures containing slag as a pozzolanic material and cured for 24 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C; the compressive strength of GS75 is maximum at 7 and 14 days but GS60 has the maximum strength at 28 days. The strength values of the mixtures having slag, hydrated lime and gypsum together are higher than that of S except for GS15 at 14 and 28 days; valid for GS60 and GS75 at 7 days. There can be an evidence of pozzolanic activity. The other explanations made for Figure 5.2 are also valid.

As can be seen from Figure 5.15, for mixtures having fly ash as a pozzolanic material and cured for 72 hours in a 50 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.1 are valid. There are also a few differences. The compressive strength of GF60 is maximum at 14 and 28 days but GF75 has the maximum strength at 7 days. The strength values of the mixtures having fly ash, hydrated lime and gypsum together are higher than that of F except for GF15 and GF30 at 7 and 28 days, for GF15 at 14 days.

From Figure 5.16, it can be said that for mixtures containing slag as a pozzolanic material and cured for 72 hours in a 50 ^{0}C oven, then cured in water at 20 ^{0}C; the compressive strength of GS60 is maximum for all curing days. The strength values of the mixtures having slag, hydrated lime and gypsum

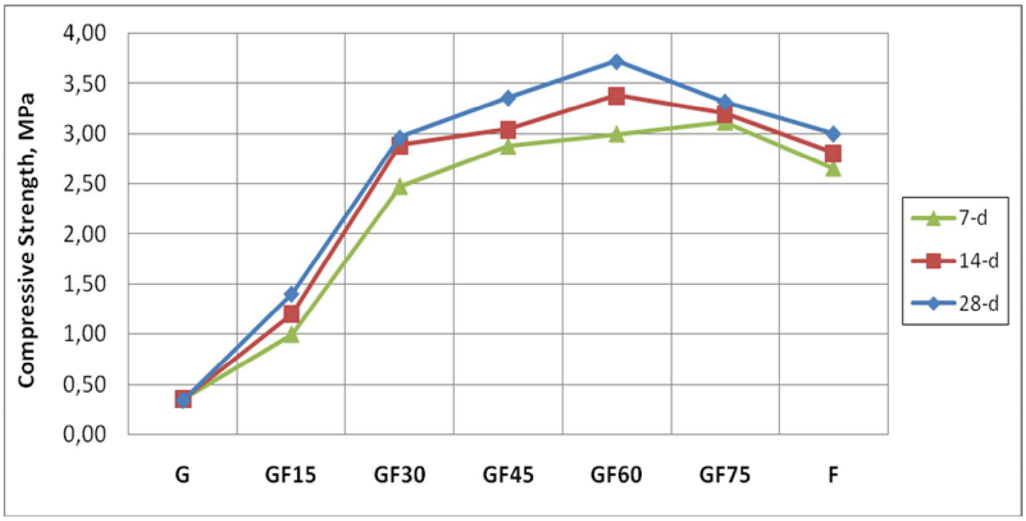

Figure 5.15 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured for 72 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

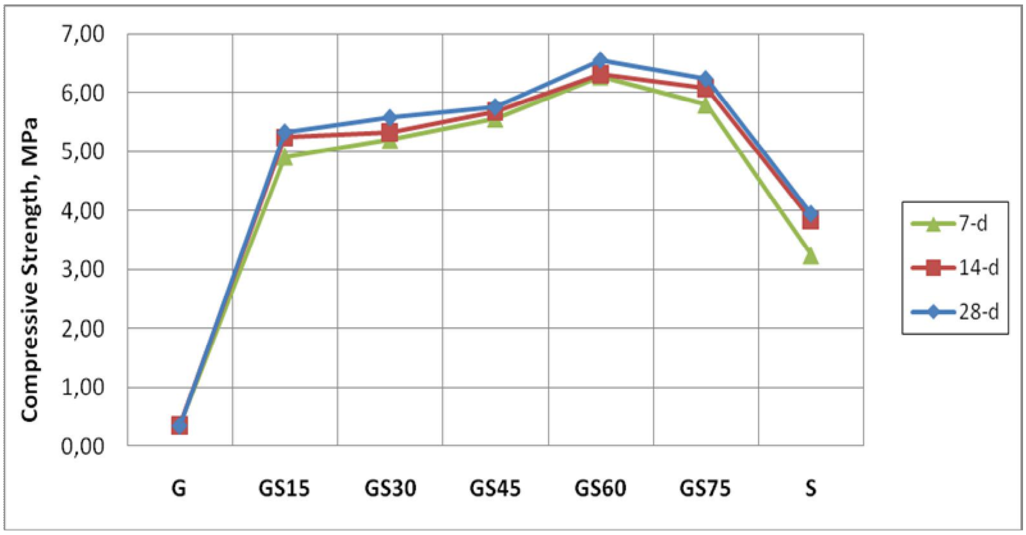

Figure 5.16 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured at 50 ^{0}C for 72 Hours in Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

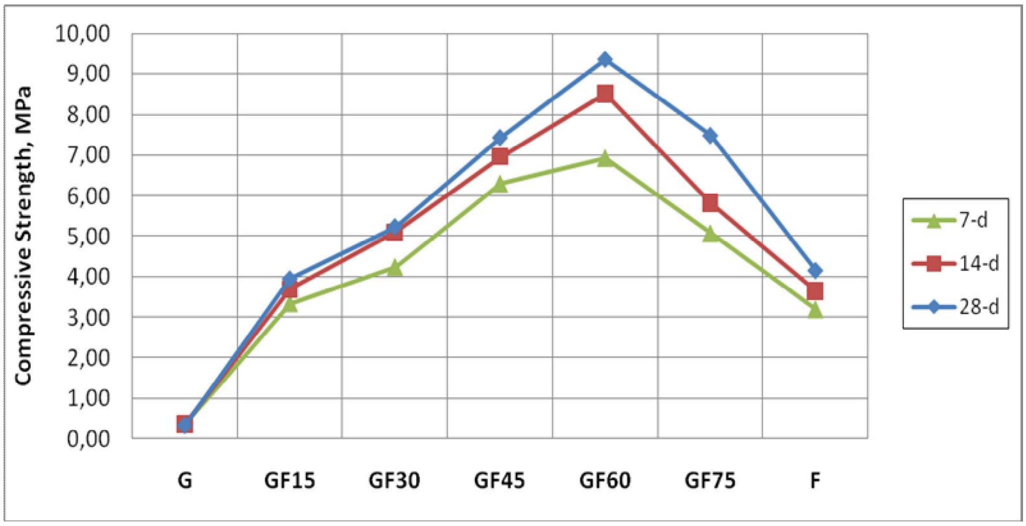

Figure 5.17 Compressive Strengths of the Mixtures Containing Gypsum, Fly Ash and Hydrated Lime Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

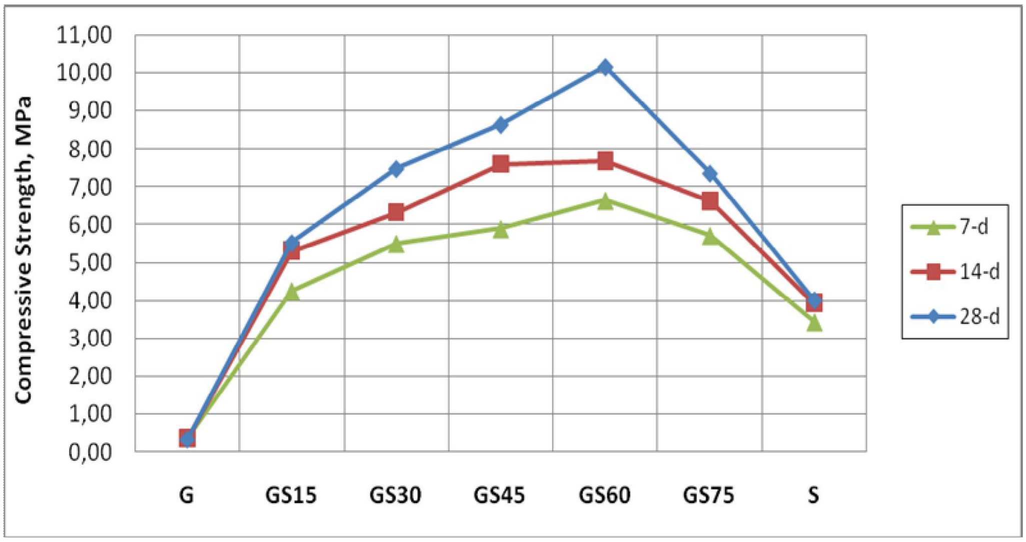

Figure 5.18 Compressive Strengths of the Mixtures Containing Gypsum, Slag and Hydrated Lime Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C at 7, 14 and 28 Days

together are higher than that of S (having slag and hydrated lime only) is valid for all mixtures and for all curing days. There can be an evidence of pozzolanic activity and this is obvious for this curing regime. The other explanations made for Figure 5.2 are also valid. The strength values at 7, 14 and 28 days are close to each other for all mixtures.

As can be seen from Figure 5.17, for mixtures having fly ash as a pozzolanic material and cured for 72 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C; the explanations made for Figure 5.1 are valid. There are also a few differences. The compressive strength of GF60 is maximum for all curing days. The strength values of the mixtures having fly ash, hydrated lime and gypsum together are higher than that of F (having fly ash and hydrated lime only) except for GF15 at 28 days.

From Figure 5.18, it can be said that for mixtures containing slag as a pozzolanic material and cured for 72 hours in an 80 ^{0}C oven, then cured in water at 20 ^{0}C; the compressive strength of GS60 is maximum for all curing days. The strength values of the mixtures having slag, hydrated lime and gypsum together are higher than that of S (having slag and hydrated lime only) valid for all mixtures and for all curing days. There is an evidence of pozzolanic activity and this is obvious for this curing regime. The other explanations made for Figure 5.2 are also valid.

5.2 Determination of the Optimum Ratios of the Materials in the Mixtures

In this part of the study, the optimum ratios of the materials which were used in the mixtures were determined to be able to get optimally performing mixtures.

The performances of the mixtures were associated with the incorporation ratios of the materials in them.

5.2.1 Determination of the Optimum Ratio of Gypsum

The relations between the performances of the mixtures and the gypsum content in them were set up. The graphs of the compressive strength of the mixtures versus gypsum content in them were obtained. By statistical analysis, the optimum gypsum contents for which mixtures showed maximum performances were determined for each mixture cured in different conditions.

The relations between the compressive strengths of the mixtures and the gypsum content in them can be seen in graphical form in the Appendix A. (Figure A.1 to Figure A.18)

As can be seen from the figures in the Appendix A, the general behavior of the mixtures is that for mixtures for which the gypsum content can be determined, as the gypsum content increases, the compressive strength of the mixtures increases up to a point, then decrease with increase of the gypsum content; for mixtures for which the gypsum content cannot be determined, as the gypsum content increases, the compressive strength of the mixtures decreases inversely.

The optimum gypsum contents in percentages by weight of the total mix, related compressive strength of the mixtures, strength increases according to strength of G (gypsum paste) cured under the same conditions, the equation of the best curve fittings (polynomial in third degree) and the correlation coefficients can be seen in the following tables.

Table 5.1 Optimum Gypsum Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 7 days

Curing Condition and Type of Pozzolan In the Mixture	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Gypsum Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^0C-F*	$y = 2E-07x^3-6E-05x^2 +0,0038x + 0,2979$	$r^2 = 0.9485$	39.44	0.37	37
50^0C-4hrs-F**	$y = 4E-07x^3-8E-05x^2 +0,0045x + 0,288$	$r^2 = 0.9450$	40.31	0.37	32
80^0C-4hrs-F	$y = 9E-08x^3-7E-05x^2 +0,005x + 0,3952$	$r^2 = 0,9374$	38.59	0.49	75
50^0C-12hrs-F	$y=3E-07x^3-7E-05x^2 +0,004x + 0,3027$	$r^2 = 0,9263$	37.72	0.37	32
80^0C-12hrs-F	$y=2E-07x^3-0,0001x^2 +0,0083x + 0,4854$	$r^2 = 0,9187$	48.58	0.68	113
50^0C-24hrs-F	$y=3E-07x^3-7E-05x^2 +0,004x + 0,3027$	$r^2 = 0,9263$	37.72	0.37	32
80^0C-24hrs-F	$y=-1E-07x^4 +2E-05x^3 -0,0013x^2+0,021x+0,9088$	$r^2 = 0,9452$	14.87	1.00	186
50^0C-72hrs-F	$y=4E-06x^3-0,0012x^2 +0,0491x+2,6202$	$r^2 = 0,9699$	23.13	3.16	803
80^0C-72hrs-F	$y=1E-05x^3 - 0,0035x^2 +0,1989x+3,0733$	$r^2 = 0,9493$	33.11	6.18	1570

*F: Fly ash, 20^0C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^0C

**50^0C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

For some mixtures, optimum gypsum contents cannot be determined because using gypsum with pozzolans and hydrated lime for these mixtures cannot provide strength increase or can provide a very small amount of increase compared to strength of the mixtures containing only pozzolans and hydrated lime.

As can be seen from Table 5.1 to 5.6, for all mixtures in different curing regimes, the strengths of the mixtures are very high according to strength of the gypsum paste cured under the same conditions. This is proof of improving of strength and water resistance of gypsum by pozzolan incorporation and elevated temperature curing.

It can be seen from Table 5.1, optimum gypsum contents are nearly between 30% and 40% except for three mixtures. The strength of the gypsum paste increases up to nearly 16 times with the addition of fly ash and hydrated lime with elevated temperature curing.

From Table 5.2, it can be said that, optimum gypsum contents are nearly between 28% and 46% except for one mix. The strength of the gypsum paste increases up to nearly 21 times with the addition of fly ash and hydrated lime with elevated temperature curing.

It can be seen from Table 5.3, optimum gypsum contents are nearly between 25% and 40% except for two mixtures. The strength of the gypsum paste increases up to nearly 25 times with the addition of fly ash and hydrated lime with elevated temperature curing.

It can be said from Table 5.1 to 5.3, the extension of curing period increased the strength of the mixtures highly compared to the strength of gypsum.

Table 5.2 Optimum Gypsum Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 14 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Gypsum Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^0C-F*	$y = 1E\text{-}07x^3 - 6E\text{-}05x^2 + 0{,}0042x + 0{,}3146$	$r^2 = 0.8974$	38.75	0.39	50
50^0C-4hrs-F**	$y = 1E\text{-}07x^3 - 5E\text{-}05x^2 + 0{,}0032x + 0{,}3248$	$r^2 = 0.9396$	35.86	0.38	40
80^0C-4hrs-F	$y = -6E\text{-}07x^3 + 6E\text{-}05x^2 - 0{,}0017x + 0{,}5097$	$r^2 = 0{,}9185$	46.24	0.50	85
50^0C-12hrs-F	$y = 1E\text{-}07x^3 - 5E\text{-}05x^2 + 0{,}0027x + 0{,}3499$	$r^2 = 0{,}9539$	29.63	0.39	44
80^0C-12hrs-F	$y = -8E\text{-}07x^3 + 4E\text{-}05x^2 + 0{,}001x + 0{,}6107$	$r^2 = 0{,}9442$	43.02	0.66	144
50^0C-24hrs-F	$y = -2E\text{-}07x^3 - 5E\text{-}05x^2 + 0{,}0048x + 0{,}4844$	$r^2 = 0{,}9687$	38.90	0.58	115
80^0C-24hrs-F	$y = -4E\text{-}07x^4 + 7E\text{-}05x^3 - 0{,}0048x^2 + 0{,}0768x + 2{,}2936$	$r^2 = 0{,}9762$	13.57	2.60	713
50^0C-72hrs-F	$y = 3E\text{-}06x^3 - 0{,}001x^2 + 0{,}0495x + 2{,}7435$	$r^2 = 0{,}9623$	28.37	3.38	865
80^0C-72hrs-F	$y = 2E\text{-}05x^3 - 0{,}0044x^2 + 0{,}2475x + 3{,}462$	$r^2 = 0{,}9400$	37.94	7.61	2074

*F: Fly ash, 20^0C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^0C

**50^0C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

Table 5.3 Optimum Gypsum Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 28 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Gypsum Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^{0}C-F	$y = 1E\text{-}08x^3 - 5E\text{-}05x^2 + 0{,}0039x + 0{,}3291$	$r^2 = 0.9769$	39.47	0.41	52
50^{0}C-4hrs-F	$y = -6E\text{-}08x^3 - 2E\text{-}05x^2 + 0{,}0013x + 0{,}4001$	$r^2 = 0.9498$	27.85	0.42	56
80^{0}C-4hrs-F	$y = -8E\text{-}07x^3 + 5E\text{-}05x^2 - 0{,}0004x + 0{,}5162$	$r^2 = 0{,}8886$	37.18	0.53	96
50^{0}C-12hrs-F	$y = 6E\text{-}08x^3 - 4E\text{-}05x^2 + 0{,}0017x + 0{,}4121$	$r^2 = 0{,}9482$	22.38	0.43	59
80^{0}C-12hrs-F	$y = 7E\text{-}08x^3 - 8E\text{-}05x^2 + 0{,}0026x + 0{,}7925$	$r^2 = 0{,}9687$	16.61	0.81	200
50^{0}C-24hrs-F	$y = 2E\text{-}06x^3 - 0{,}0005x^2 + 0{,}021x + 0{,}7794$	$r^2 = 0{,}9637$	24.64	1.02	278
80^{0}C-24hrs-F	$y = -3E\text{-}06x^3 - 0{,}0048x^2 + 0{,}0163x + 3{,}1817$	$r^2 = 0{,}9430$	32.87	3.50	900
50^{0}C-72hrs-F	$y = 3E\text{-}06x^3 - 0{,}0011x^2 + 0{,}0531x + 2{,}9192$	$r^2 = 0{,}9747$	27.15	3.61	962
80^{0}C-72hrs-F	$y = 3E\text{-}05x^3 - 0{,}0059x^2 + 0{,}2980x + 4{,}1504$	$r^2 = 0{,}9612$	34.14	8.64	2441

*F: Fly ash, 20^{0}C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^{0}C

**50^{0}C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

As can be seen from Table 5.4 to 5.6 for some mixtures optimum gypsum contents can be determined. For other mixtures, using gypsum with pozzolans and hydrated lime cannot provide strength increase or can provide a small amount of increase compared to strength of the mixtures containing only pozzolans and hydrated lime.

It can be seen from Table 5.4, optimum gypsum contents are nearly between 30% and 45%. The strength of the gypsum paste increases up to nearly 17 times with the addition of slag and hydrated lime by curing at elevated temperatures.

Table 5.4 Optimum Gypsum Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 7 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Gypsum Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
80^{0}C-24hrs-S*	$y=-5E-06x^{3}-0,0002x^{2}+0,0024x+3,2876$	$r^2 = 0,9444$	31.71	3.40	871
50^{0}C-72hrs-S	$y=-4E-06x^{3}-0,001x^{2}+0,1167x+3,4689$	$r^2 = 0,9230$	45.78	6.33	1709
80^{0}C-72hrs-S	$y=-3E-07x^{3}-0,0017x^{2}+0,1394x+3,5305$	$r^2 = 0,9776$	40.56	6.38	1624

*S: Slag, 80^{0}C-24hrs-S : Mixtures containing slag as a pozzolanic material, cured at 80 ^{0}C for 24 hours in oven then cured in water at 20 ^{0}C

It can be seen from Table 5.5, optimum gypsum contents are nearly between 35% and 47%. The strength of the gypsum paste increases up to nearly 21 times with the addition of slag and hydrated lime by curing at elevated temperatures.

Table 5.5 Optimum Gypsum Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 14 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Gypsum Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
80^0C-24hrs-S*	$y=-3E-06x^3-0,0005x^2+0,046x+3,7981$	$r^2 = 0,9668$	34.98	4.67	1359
50^0C-72hrs-S	$y=-8E-06x^3-0,0003x^2+0,0815x+4,0975$	$r^2 = 0,9103$	47.10	6.43	1737
80^0C-72hrs-S	$y=-2E-06x^3-0,0018x^2+0,1672x+4,0006$	$r^2 = 0,9806$	43.32	7.70	2100

*S: Slag, 80^0C-24hrs-S : Mixtures containing slag as a pozzolanic material, cured at 80 ^{0}C for 24 hours in oven then cured in water at 20 ^{0}C

As can be seen from Table 5.6, optimum gypsum contents are nearly between 40% and 45% except for one mix. The strength of the gypsum paste increases up to nearly 27 times with the addition of slag and hydrated lime by curing at elevated temperatures.

Table 5.6 Optimum Gypsum Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 28 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Gypsum Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
50^{0}C-24hrs-S*	$y=-3E-06x^3-9E-05x^2+0,082x+3,7808$	$r^2 = 0,9739$	21.80	3.88	1337
80^{0}C-24hrs-S	$y=-2E-06x^3-0,001x^2+0,0898x+3,9983$	$r^2 = 0,9935$	40.08	5.86	1574
50^{0}C-72hrs-S	$y=-9E-06x^3-0,0003x^2+0,0842x+4,2117$	$r^2 = 0,9144$	45.83	6.57	1832
80^{0}C-72hrs-S	$y=-2E-06x^3-0,0018x^2+0,1672x+4,0006$	$r^2 = 0,9672$	40.38	9.63	2732

*S: Slag, 50^{0}C-24hrs-S : Mixtures containing slag as a pozzolanic material, cured at 50 ^{0}C for 24 hours in oven then cured in water at 20 ^{0}C

It can be seen from Table 5.4 to 5.6, the increase in age, increased the strength of the mixtures highly compared to the strength of gypsum.

5.2.2 Determination of the Optimum Ratio of Pozzolans

5.2.2.1 Determination of the Optimum Ratio of Fly Ash

The relations between the performances of the mixtures and the fly ash content in them were set up. The graphs of the compressive strength of the mixtures versus fly ash content in them were obtained. By statistical analysis, the optimum fly ash contents for which mixtures showed maximum performances were determined for each mixture cured in different conditions.

The relations between the compressive strength of the mixtures and the fly ash content in them can be seen in graphical form in the Appendix A. (Figure A.19 to Figure A.27)

As can be seen from the figures in the Appendix A, the general behavior of the mixtures is that for mixtures for which the fly ash content can be determined; as the fly ash content increases, the compressive strength of the mixtures increases up to a point, then decrease with increase of the fly ash content. Also, for fly ash contents, the maximum value of them is 71.43% of the total mix by weight because for all mixtures pozzolans were used with hydrated lime (40% of the pozzolans by weight) together.

The optimum fly ash contents in percentages by weight of the total mix, related compressive strength of the mixtures, strength increases according to strength of the G (gypsum paste) cured under the same conditions, the equation of the best curve fittings (polynomial in third degree) and the correlation coefficients can be seen in the following tables.

As can be seen from Table 5.7 to 5.9, for all mixtures in different curing regimes, the strengths of the mixtures are very high according to strength of the G (gypsum paste) cured under the same conditions. This is a proof of improving of strength and water resistance of gypsum by pozzolan incorporation and elevated temperature curing.

As can be seen from Table 5.7, optimum fly ash contents are nearly between

Table 5.7 Optimum Fly Ash Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 7 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Fly Ash Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^0C-F*	$y = -7E\text{-}07x^3 - 6E\text{-}05x^2 + 0,0028x + 0,2678$	$r^2 = 0.9485$	41.59	0.35	29
50^0C-4hrs-F**	$y = -1E\text{-}06x^3 + 5E\text{-}05x^2 + 0,0017x + 0,2777$	$r^2 = 0.9450$	45.73	0.36	28
80^0C-4hrs-F	$y = -2E\text{-}07x^3 - 9E\text{-}05x^2 + 0,009x + 0,2816$	$r^2 = 0,9374$	43.65	0.49	75
50^0C-12hrs-F	$y = -7E\text{-}07x^3 + 2E\text{-}05x^2 + 0,0025x + 0,2835$	$r^2 = 0,9263$	45.32	0.37	32
80^0C-12hrs-F	$y = -5E\text{-}07x^3 - 0,0001x^2 + 0,0131x + 0,3336$	$r^2 = 0,9187$	48.13	0.63	97
50^0C-24hrs-F	$y = -7E\text{-}07x^3 + 2E\text{-}05x^2 + 0,0025x + 0,2835$	$r^2 = 0,9263$	45.32	0.37	32
80^0C-24hrs-F	$y = -4E\text{-}07x^4 + 6E\text{-}05x^3 - 0,0026x^2 + 0,0454x + 0,3409$	$r^2 = 0,9452$	62.58	1.00	186
50^0C-72hrs-F	$y = -1E\text{-}05x^3 - 0,0003x^2 + 0,0719x + 2,618$	$r^2 = 0,9675$	55.69	3.13	794
80^0C-72hrs-F	$y = -3E\text{-}05x^3 - 0,0003x^2 + 0,1837x + 0,4277$	$r^2 = 0,9493$	48.63	6.62	1689

*F: Fly ash, 20^0C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^0C

**50^0C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

Table 5.8 Optimum Fly Ash Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 14 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Fly Ash Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^0C-F*	$y=-4E-07x^3-4E-05x^2 +0{,}0057x + 0{,}2573$	$r^2 = 0.8974$	43.22	0.40	54
50^0C-4hrs-F**	$y=-4E-07x^3-2E-05x^2 +0{,}0042x + 0{,}2663$	$r^2 = 0.9396$	44.80	0.38	40
80^0C-4hrs-F	$y=2E-06x^3-0{,}0003x^2 +0{,}0134x + 0{,}268$	$r^2 = 0{,}9185$	33.67	0.46	70
50^0C-12hrs-F	$y=-3E-07x^3-3E-05x^2 +0{,}0045x + 0{,}2728$	$r^2 = 0{,}9539$	44.84	0.39	44
80^0C-12hrs-F	$y=2E-06x^3-0{,}0004x^2 +0{,}0219x + 0{,}2814$	$r^2 = 0{,}9442$	38.48	0.65	141
50^0C-24hrs-F	$y=5E-07x^3-0{,}0002x^2 +0{,}0149x + 0{,}2789$	$r^2 = 0{,}9687$	44.76	0.59	119
80^0C-24hrs-F	$y=-1E-06x^4 +0{,}0002x^3 -0{,}0026x^2+0{,}0454x +0{,}3409$	$r^2 = 0{,}9762$	64.13	2.60	713
50^0C-72hrs-F	$y=-8E-05x^3-0{,}0003x^2 +0{,}0985x+0{,}251$	$r^2 = 0{,}9623$	52.77	3.44	883
80^0C-72hrs-F	$y=-4E-05x^3 +0{,}001x^2 +0{,}2027x+0{,}4064$	$r^2 = 0{,}9400$	50.26	8.04	2197

*F: Fly ash, 20^0C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^0C

**50^0C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

Table 5.9 Optimum Fly Ash Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 28 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Fly Ash Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^0C-F*	$y=-3E-08x^3-8E-05x^2$ $+0,0069x+0,2699$	$r^2=0.9769$	42.13	0.42	56
50^0C-4hrs-F**	$y=2E-07x^3-7E-05x^2$ $+0,0062x+0,2736$	$r^2=0.9498$	59.41	0.43	59
80^0C-4hrs-F	$y=2E-06x^3+0,0003x^2$ $-0,017x+0,2645$	$r^2=0,8886$	32.26	0.53	96
50^0C-12hrs-F	$y=-2E-07x^3-4E-05x^2$ $+0,0054x+0,2751$	$r^2=0,9482$	49.28	0.42	56
80^0C-12hrs-F	$y=-2E-07x^3-0,0001x^2$ $+0,0168x+0,2879$	$r^2=0,9687$	69.50	0.81	200
50^0C-24hrs-F	$y=-5E-06x^3+0,0003x^2$ $+0,0155x+0,2961$	$r^2=0,9637$	57.86	1.08	300
80^0C-24hrs-F	$y=9E-06x^3-0,0021x^2$ $+0,01443x+0,4828$	$r^2=0,9430$	51.22	3.57	920
50^0C-72hrs-F	$y=-8E-06x^3-0,0005x^2$ $+0,1107x+0,2495$	$r^2=0,9747$	50.20	3.53	938
80^0C-72hrs-F	$y=-7E-05x^3+0,0036x^2$ $+0,1563x+0,5239$	$r^2=0,9612$	49.36	8.59	2426

*F: Fly ash, 20^0C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^0C

**50^0C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

40% and 50% except for two mixtures. The strength of the gypsum paste increases up to nearly 17 times with the addition of fly ash and hydrated lime by curing at elevated temperatures.

From Table 5.8, it can be said that, optimum fly ash contents are nearly between 43% and 53% except for three mixtures. The strength of the gypsum paste increases up to nearly 22 times with the addition of fly ash and hydrated lime by curing at elevated temperatures.

It can be seen from Table 5.9, optimum fly ash contents are nearly between 49% and 60% except for three mixtures. The strength of the gypsum paste increases up to nearly 25 times with the addition of fly ash and hydrated lime by curing at elevated temperatures.

It can be said from Table 5.7 to 5.9, the extension of curing period increased the strength of the mixtures highly compared to the strength of gypsum.

5.2.2.2 Determination of the Optimum Ratio of Slag

The relations between the performances of the mixtures and slag content in them were set up. The graphs of the compressive strength of the mixtures versus slag content in them were obtained. By statistical analysis, the optimum slag contents for which mixtures showed maximum performances were determined for each mixture cured in different conditions.

The relations between the compressive strength of the mixtures and the slag content in them can be seen in graphical form in the Appendix A. (Figure A.28 to Figure A.36)

As can be seen from the figures in the Appendix A, the general behavior of the mixtures is that for mixtures for which the slag content can be determined; as the slag content increases, the compressive strength of the mixtures increases up to a point, then decrease with increase of the slag content, for mixtures for which the slag content cannot be determined; as the slag content increases, the compressive strength of the mixtures decreases inversely. Also, for slag contents like fly ash contents, the maximum value of them is 71.43% of the total mix by weight because for all mixtures pozzolans with hydrated lime (40% of the pozzolans by weight) were used together.

The optimum slag contents in percentages by weight of the total mix, related compressive strength of the mixtures, strength increases according to strength of the gypsum paste cured under the same conditions, the equation of the best curve fittings (polynomial in third degree) and the correlation coefficients can be seen in the following tables.

For some mixtures, optimum slag contents cannot be determined because using gypsum with pozzolans and hydrated lime for these mixtures cannot provide strength increase or can provide a small amount of increase compared to strength of the mixtures containing pozzolans and hydrated lime only. On the other hand, for all mixtures in different curing regimes, the strengths of the mixtures are very high according to strength of the gypsum paste cured under the same conditions. This is a proof of improving of strength and water resistance of gypsum by pozzolan incorporation and elevated temperature curing.

As can be seen from Table 5.10, optimum slag contents are nearly between 38% and 42% except for one mix. The strength of the gypsum paste increases up to nearly 17 times with the addition of slag and hydrated lime by curing at elevated temperatures.

Table 5.10 Optimum Slag Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 7 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Slag Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
80^0C-12hrs-S*	$y=-3E\text{-}05x^3+0{,}0029x^2+0{,}0441x+0{,}4218$	$r^2 = 0{,}8834$	55.63	1.78	456
80^0C-24hrs-S	$y=1E\text{-}05x^3+0{,}0026x^2+0{,}1543x+0{,}4794$	$r^2 = 0{,}9444$	38.00	3.14	797
50^0C-72hrs-S	$y=1E\text{-}05x^3-0{,}0044x^2+0{,}299x+0{,}6407$	$r^2 = 0{,}9230$	39.22	6.20	1671
80^0C-72hrs-S	$y=9E\text{-}07x^3-0{,}0035x^2+0{,}2845x+0{,}5069$	$r^2 = 0{,}9776$	41.30	6.35	1616

*S: Slag, 80^0C-12hrs-S : Mixtures containing slag as a pozzolanic material, cured at 80 ^{0}C for 12 hours in oven then cured in water at 20 ^{0}C

It can be seen from Table 5.11, optimum slag contents are nearly between 37% and 47% except for one mix.

The strength of the gypsum paste increases up to nearly 21 times with the addition of slag and hydrated lime by curing at elevated temperatures.

As can be seen from Table 5.12, optimum slag contents are nearly between 36% and 45% except for one mix.

The strength of the gypsum paste increases up to nearly 27 times with the addition of slag and hydrated lime by curing at elevated temperatures.

Table 5.11 Optimum Slag Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 14 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Slag Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
80^{0}C-12hs-S*	$y=-2E-05x^3+0,0018x^2-0,0025x+0,3772$	$r^2 = 0,8834$	59.30	2.38	781
80^{0}C-24hrs-S	$y=8E-06x^3-0,0027x^2+0,1983x+0,4117$	$r^2 = 0,9668$	46.21	4.60	1338
50^{0}C-72hrs-S	$y=2E-05x^3-0,0055x^2+0,3263x+0,6694$	$r^2 = 0,9103$	37.22	6.22	1677
80^{0}C-72hrs-S	$y=6E-06x^3-0,0049x^2+0,3638x+4,0006$	$r^2 = 0,9806$	40.07	7.61	2074

*S: Slag, 80^{0}C-12hrs-S : Mixtures containing slag as a pozzolanic material, cured at 80 ^{0}C for 12 hours in oven then cured in water at 20 ^{0}C

It can be said from Table 5.10 to 5.12, the extension of curing period increased the strength of the mixtures highly compared to the strength of the gypsum paste.

Table 5.12 Optimum Slag Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 28 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum Slag Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
50^0C-24hrs-S*	$y=9E-06x^3-0,0021x^2+0,1541x+0,3586$	$r^2 = 0,9739$	59.28	3.98	1374
80^0C-24hrs-S	$y=6E-06x^3-0,0034x^2+0,2589x+0,3813$	$r^2 = 0,9935$	42.96	5.74	1540
50^0C-72hrs-S	$y=2E-05x^3-0,0057x^2+0,3382x+0,6568$	$r^2 = 0,9144$	36.79	6.38	1776
80^0C-72hrs-S	$y=-2E-05x^3-0,0028x^2+0,3687x+0,4627$	$r^2 = 0,9672$	44.56	9.56	2712

*S: Slag, 50^0C-24hrs-S : Mixtures containing slag as a pozzolanic material, cured at 50 ^{0}C for 24 hours in oven then cured in water at 20 ^{0}C

5.2.3 Determination of the Optimum Ratio of Hydrated Lime

The relations between the performances of the mixtures and the hydrated lime content in them were set up. The graphs of the compressive strength of the mixtures versus content in them were obtained. By statistical analysis, the optimum hydrated lime contents for which mixtures showed maximum performances were determined for each mixture cured in different conditions.

The relations between the compressive strength of the mixtures and the hydrated lime content in them can be seen in graphical form in the Appendix A. (Figure A.37 to Figure A.54)

As can be seen from the figures in the Appendix A, the general behavior of the mixtures is that for mixtures for which hydrated lime content can be determined; as hydrated lime content increases, the compressive strength of the mixtures increases up to a point, then decrease with increase of hydrated lime content, for mixtures for which hydrated lime content cannot be determined; as the hydrated lime content increases, the compressive strength of the mixtures increases.

The optimum hydrated lime contents in percentages by weight of the total mix, related compressive strength of the mixtures, strength increases according to strength of the G (gypsum paste) cured under the same conditions, the equation of the best curve fittings (polynomial in third degree) and the correlation coefficients can be seen in the following tables.

For some mixtures, optimum hydrated lime contents can be determined because using gypsum with pozzolans and hydrated lime for other mixtures cannot provide strength increase or can provide a small amount of increase compared to strength of the mixtures containing only pozzolans and hydrated lime. On the other hand, all mixtures have higher strength values than those of gypsum paste under all curing conditions. This is an indication of improving of strength and water resistance of gypsum by pozzolan incorporation and elevated temperature curing. Also, for hydrated lime contents, the maximum value of them is 28.57% of the total mix by weight because for all mixtures pozzolans with hydrated lime (40% of the pozzolans by weight) were used together.

Table 5.13 Optimum Hydrated Lime Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 7 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum CH* Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^0C-F**	$y=-1E-05x^3+8E-05x^2+0{,}0070x+0{,}2678$	$r^2=0.9485$	18.17	0.36	33
50^0C-4hrs-F***	$y=-2E-05x^3+0{,}0003x^2+0{,}0043x+0{,}2777$	$r^2=0.9450$	14.83	0.34	21
80^0C-4hrs-F	$y=-4E-06x^3-0{,}0005x^2+0{,}0224x+0{,}2816$	$r^2=0{,}9374$	18.35	0.49	75
50^0C-12hrs-F	$y=-1E-05x^3+0{,}0001x^2+0{,}0062x+0{,}2835$	$r^2=0{,}9263$	18.09	0.37	32
80^0C-12hrs-F	$y=-8E-06x^3-0{,}0007x^2+0{,}0328x+0{,}3336$	$r^2=0{,}9187$	17.92	0.65	103
50^0C-24hrs-F	$y=-1E-05x^3+0{,}0001x^2+0{,}0062x+0{,}2835$	$r^2=0{,}9263$	18.09	0.39	39
80^0C-24hrs-F	$y=-2E-05x^4+0{,}0009x^3-0{,}0164x^2+0{,}1135x+0{,}3409$	$r^2=0{,}9452$	25.12	1.00	186
50^0C-72hrs-F	$y=-0{,}0002x^3-0{,}0021x^2+0{,}1798x+2{,}618$	$r^2=0{,}9699$	21.16	3.11	789
80^0C-72hrs-F	$y=-0{,}0005x^3+0{,}0019x^2+0{,}4593x+4{,}277$	$r^2=0{,}9493$	18.80	6.41	1632

*CH: Hydrated lime

**20^0C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^0C

***50^0C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

Table 5.14 Optimum Hydrated Lime Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 14 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum CH* Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^0C-F**	$y=-6E-06x^3-0,0003x^2+0,0142x+0,2573$	$r^2 = 0.8974$	15.99	0.38	46
50^0C-4hrs-F***	$y=-6E-06x^3-0,0001x^2+0,0104x+0,2663$	$r^2 = 0.9396$	19.11	0.39	44
80^0C-4hrs-F	$y=3E-05x^3+0,0017x^2+0,0334x+0,268$	$r^2 = 0,9185$	18.89	0.49	85
50^0C-12hrs-F	$y=-5E-06x^3-0,0002x^2+0,0112x+0,2728$	$r^2 = 0,9539$	17.07	0.38	41
80^0C-12hrs-F	$y=3E-05x^3+-0,0025x^2+0,0547x+0,2814$	$r^2 = 0,9442$	14.98	0.64	137
50^0C-24hrs-F	$y=7E-06x^3-0,0013x^2+0,0371x+0,2789$	$r^2 = 0,9687$	16.46	0.59	119
80^0C-24hrs-F	$y=-6E-05x^4+0,0031x^3-0,0551x^2+0,3774x+0,3051$	$r^2 = 0,9762$	25.72	2.60	713
50^0C-72hrs-F	$y=-0,0001x^3-0,002x^2+0,2462x+0,2510$	$r^2 = 0,9623$	22.75	3.37	863
80^0C-72hrs-F	$y=-0,0007x^3+0,0061x^2+0,5067x+0,4064$	$r^2 = 0,9400$	18.70	7.43	2023

*CH: Hydrated lime

**20^0C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^0C

***50^0C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

Table 5.15 Optimum Hydrated Lime Contents in the Mixtures Containing Fly Ash as a Pozzolanic Material, Providing Optimum Performances at 28 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum CH* Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
20^0C-F**	$y = -5E-07x^3 - 0,0005x^2 + 0,0173x + 0,2699$	$r^2 = 0.9769$	16.87	0.42	55
50^0C-4hrs-F***	$y = 3E-06x^3 - 0,0005x^2 + 0,0155x + 0,2736$	$r^2 = 0.9498$	18.62	0.42	56
80^0C-4hrs-F	$y = 3E-05x^3 + 0,0021x^2 + 0,0426x + 0,2645$	$r^2 = 0,8886$	14.90	0.53	96
50^0C-12hrs-F	$y = -3E-06x^3 - 0,0002x^2 + 0,0134x + 0,2751$	$r^2 = 0,9482$	22.31	0.44	62
80^0C-12hrs-F	$y = -3E-06x^3 - 0,0008x^2 + 0,042x + 0,2879$	$r^2 = 0,9687$	23.22	0.79	192
50^0C-24hrs-F	$y = -8E-05x^3 - 0,0016x^2 + 0,0387x + 0,2961$	$r^2 = 0,9637$	21.01	1.05	288
80^0C-24hrs-F	$y = 0,0001x^3 - 0,0133x^2 + 0,3608x + 0,4828$	$r^2 = 0,9430$	16.71	3.45	885
50^0C-72hrs-F	$y = -0,0001x^3 - 0,0031x^2 + 0,2768x + 0,2495$	$r^2 = 0,9747$	21.75	3.64	970
80^0C-72hrs-F	$y = -0,0011x^3 + 0,0225x^2 + 0,3906x + 0,5239$	$r^2 = 0,9612$	19.66	8.54	2411

*CH: Hydrated lime

**20^0C-F: Mixtures containing fly ash as a pozzolanic material, cured at 20^0C

***50^0C-4hrs-F: Mixtures containing fly ash as a pozzolanic material, cured at 50 ^{0}C for 4 hours in oven then cured in water at 20 ^{0}C

It can be seen from Table 5.13, optimum hydrated lime contents are nearly between 17% and 22% except for two mixtures.

The strength of the gypsum paste increases up to nearly 16 times with the addition of fly ash and hydrated lime by curing at elevated temperatures.

From Table 5.14, it can be said that, optimum hydrated lime contents are nearly between 15% and 20% except for two mixtures.

The strength of the gypsum paste increases up to nearly 21 times with the addition of fly ash and hydrated lime by curing at elevated temperatures.

It can be seen from Table 5.15, optimum hydrated lime contents are nearly between 15% and 23%.

The strength of the gypsum paste increases up to nearly 25 times with the addition of fly ash and hydrated lime by curing at elevated temperatures.

It can be said from Table 5.13 to 5.15, the extension of curing period increased the strength of the mixtures highly according to the strength of gypsum.

As can be seen from Table 5.16, optimum hydrated lime contents are nearly between 16% and 17%.

The strength of the gypsum paste increases up to nearly 17 times with the addition of slag and hydrated lime by curing at elevated temperatures.

It can be seen from Table 5.17, optimum hydrated lime contents are nearly between 16% and 18%.

The strength of the gypsum paste increases up to nearly 21 times with the addition of slag and hydrated lime by curing at elevated temperatures.

As can be seen from Table 5.18, optimum hydrated lime contents are nearly between 16% and 18%.

The strength of the gypsum paste increases up to nearly 26 times with the addition of slag and hydrated lime by curing at elevated temperatures

Table 5.16 Optimum Hydrated Lime Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 7 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum CH* Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
80^0C-24hrs-S**	$y=0,0002x^3+0,0164x^2+0,3857x+0,4794$	$r^2 = 0,9444$	17.12	3.27	834
50^0C-72hrs-S	$y=0,0002x^3-0,0276x^2+0,7475x+0,6407$	$r^2 = 0,9230$	16.50	6.35	1714
80^0C-72hrs-S	$y=1E-05x^3-0,0216x^2+0,7113x+0,5069$	$r^2 = 0,9776$	16.66	6.41	1632

*CH: Hydrated lime

**S: Slag, 80^0C-24hrs-S : Mixtures containing slag as a pozzolanic material, cured at 80 ^{0}C for 24 hours in oven then cured in water at 20 ^{0}C

Table 5.17 Optimum Hydrated Lime Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 14 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum CH* Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
80^0C-24hrs-S**	$y=1E\text{-}04x^3-0{,}0166x^2+0{,}4957x+0{,}4117$	$r^2 = 0{,}9668$	17.79	4.53	1316
50^0C-72hrs-S	$y=4E\text{-}04x^3-0{,}0345x^2+0{,}8158x+0{,}6694$	$r^2 = 0{,}9103$	16.63	6.55	1771
80^0C-72hrs-S	$y=1E\text{-}04x^3-0{,}0304x^2+0{,}9096x+0{,}5149$	$r^2 = 0{,}9806$	16.27	7.69	2100

*CH: Hydrated lime

**S: Slag, 80^0C-24hrs-S : Mixtures containing slag as a pozzolanic material, cured at 80 ^{0}C for 24 hours in oven then cured in water at 20 ^{0}C

It can be seen from Table 5.16 to Table 5.18, the extension of curing period increased the strength of the mixtures highly according to the strength of gypsum.

As mentioned in previous section 5.2.1, for the optimum gypsum contents of the mixes providing optimum performances, considering for all curing days, it can be said that for the mixes containing fly ash as a pozzolanic material optimum gypsum contents are between 25% and 46% of the mixes by weight; on the other hand, for the mixes containing slag as a pozzolanic material optimum gypsum contents are between 30% and 47% of the mixes by weight.

Table 5.18 Optimum Hydrated Lime Contents in the Mixtures Containing Slag as a Pozzolanic Material, Providing Optimum Performances at 28 days

Curing Condition and Type of Pozzolan In the Mix	Equation of the Best Curve Fitting	Correlation Coefficient (r^2)	Optimum CH* Content (%)	Related Compres. Strength (MPa)	Strength Increase (%)
50^{0}C-24hrs-S**	$y=1E-04x^3-0,0134x^2$ $+0,3852x+0,3586$	$r^2 = 0,9739$	18.00	3.80	1307
80^{0}C-24hrs-S	$y=1E-04x^3-0,021x^2$ $+0,6473x+0,3813$	$r^2 = 0,9935$	17.63	5.81	1560
50^{0}C-72hrs-S	$y=4E-04x^3-0,0358x^2$ $+0,8454x+0,6568$	$r^2 = 0,9144$	16.21	6.65	1856
80^{0}C-72hrs-S	$y=-4E-04x^3-0,0175x^2$ $+0,9218x+0,4627$	$r^2 = 0,9672$	16.73	9.11	2579

*CH: Hydrated lime

**S: Slag, 50^{0}C-24hrs-S : Mixtures containing slag as a pozzolanic material, cured at 50 ^{0}C for 24 hours in oven then cured in water at 20 ^{0}C

As mentioned in previous section 5.2.2, for the optimum pozzolan contents of the mixes providing optimum performances, considering for all curing days, it can be said that for the mixes containing fly ash as a pozzolanic material optimum fly ash contents are between 43% and 60% of the mixes by weight; on the other hand, for the mixes containing slag as a pozzolanic material optimum slag contents are between 36% and 47% of the mixes by weight.

For the optimum hydrated lime contents of the mixes providing optimum performances, considering for all curing days, it can be said that for the mixes containing fly ash as a pozzolanic material optimum hydrated lime contents are between 15% and 23% of the mixes by weight; on the other hand, for the mixes containing slag as a pozzolanic material optimum hydrated lime contents are between 16% and 18% of the mixes by weight.

As a result, by taking optimum hydrated lime contents as a base due to changing in smaller ranges, also considering hydrated lime were used constantly 40% of the pozzolans by weight for all mixes, for all curing days, for the mixes containing fly ash as a pozzolanic material, 19% as hydrated lime content (mean value), 47.5% as fly ash content and 33.5% as gypsum content by weight of the mix are the optimum contents, for the mixes containing slag as a pozzolanic material, 17% as hydrated lime content (mean value), 42.5% as slag content and 40.5% as gypsum content by weight of the mix are the optimum contents.

5.3 Determination of the Effects of Elevated Temperature Curing and Type of Pozzolan on the Performances of the Mixtures Having the Same Amount of Pozzolans

In this part of the study, the effects of elevated temperature curing and the type of pozzolan on the performances of the mixtures having the same amount of pozzolans were investigated. In this way, the behavior of the mixtures having the same amount of pozzolans under high temperature curing was able to be determined.

Firstly, for the mixtures cured in a 50 ^{0}C oven for a while, then cured in water at 20 ^{0}C; as can be seen from Figure 5.19 to 5.24,

- In general, the compressive strengths of the mixtures at 7-, 14-, and 28-day increase with the extension of the curing duration in the oven.

- With the extension of the curing days it can be seen increases in strength values as an evidence of the hydration.

- For the mixtures containing slag as a pozzolanic material; in general the strength values at 14- and 28-day are close to each other and they are higher than those at 7-day but all strength values are closer to each other as the curing durations in the oven increase.

- For the mixtures containing fly ash as a pozzolanic material; the strength values for all curing days are very close to each other up to 12 hours in oven then the strength differences occur between them but these differences are very small and they decrease or become constant with the extension of the curing duration in the oven.

- The compressive strengths of the mixtures containing slag are higher than those of the mixtures containing fly ash for all curing days and the strength differences between them increase or become nearly constant with the extension of the curing duration in the oven. This can be an indication of the higher activation of the slag than fly ash for the mixtures cured in oven at 50 ^{0}C for a time then cured in water at 20 ^{0}C. On the other hand, from Figure 5.24, it can be seen that for F and S the strength differences decrease with the curing duration in the oven.

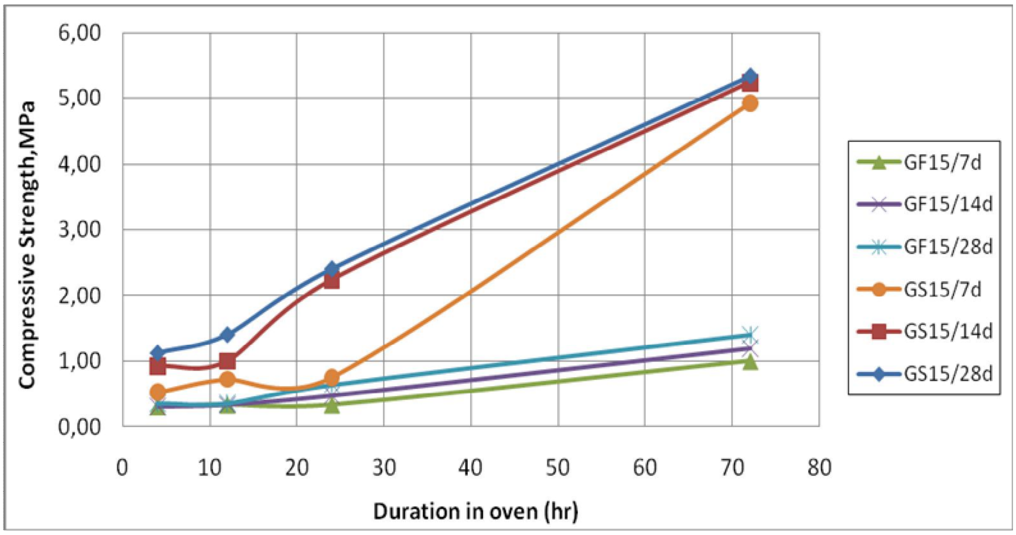

Figure 5.19 “Compressive Strength of GF15 and GS15 Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Curing Times

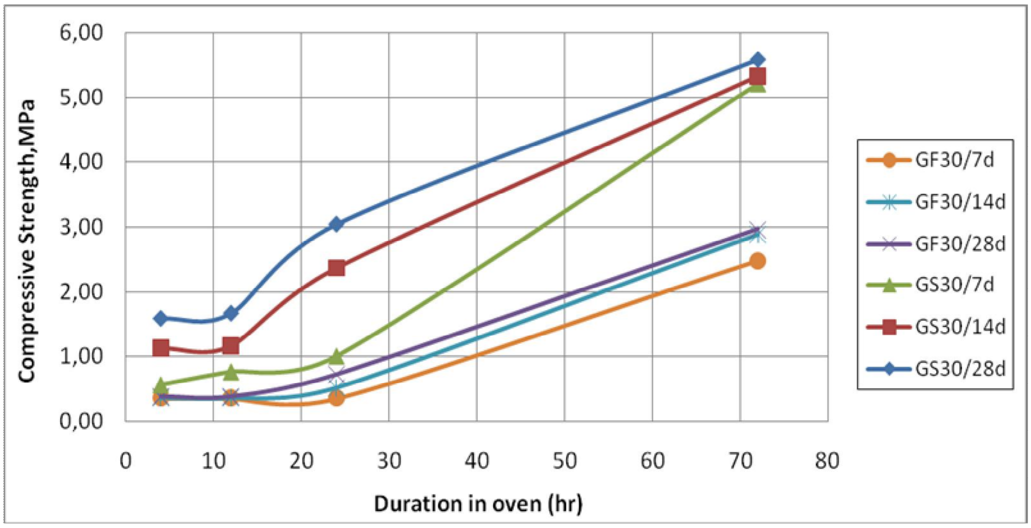

Figure 5.20 “Compressive Strength of GF30 and GS30 Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Curing Times

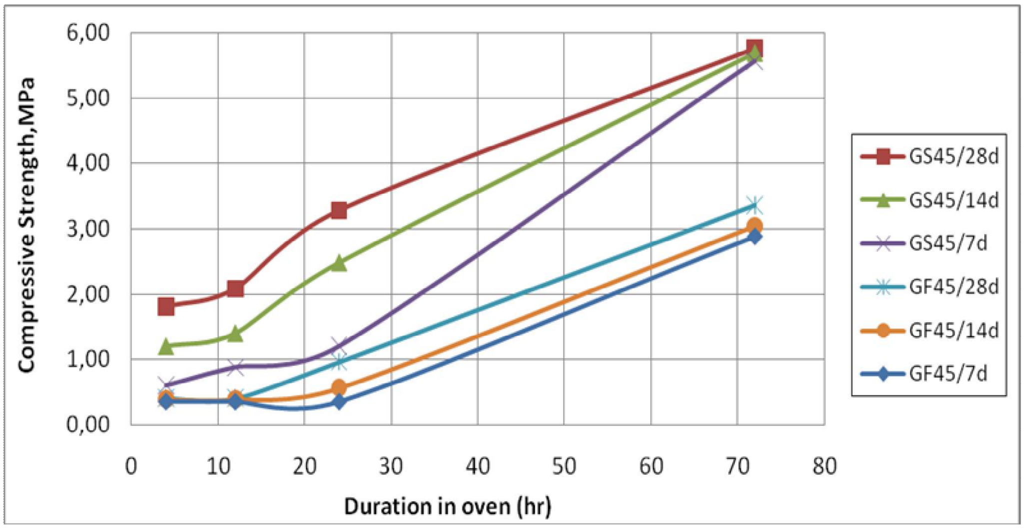

Figure 5.21 “Compressive Strength of GF45 and GS45 Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Curing Times

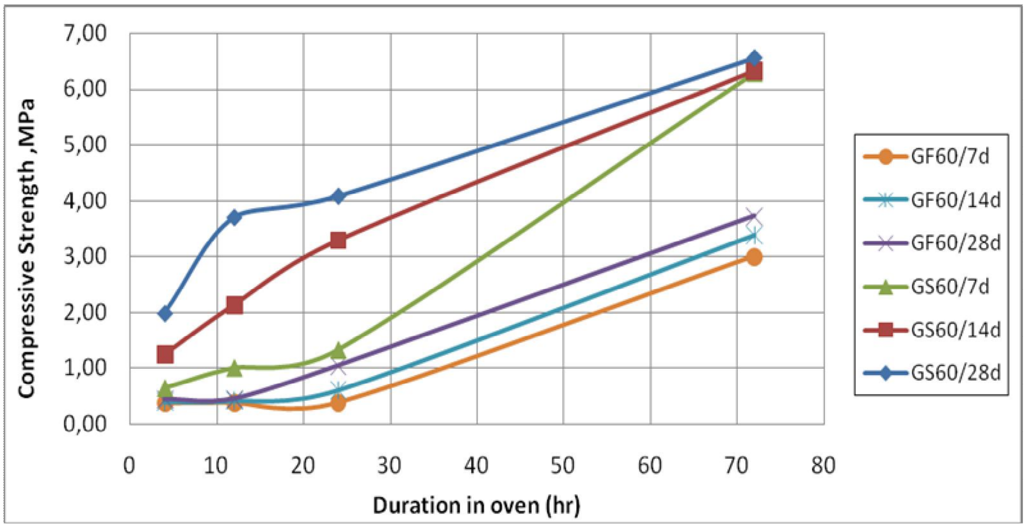

Figure 5.22 “Compressive Strength of GF60 and GS60 Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Curing Times

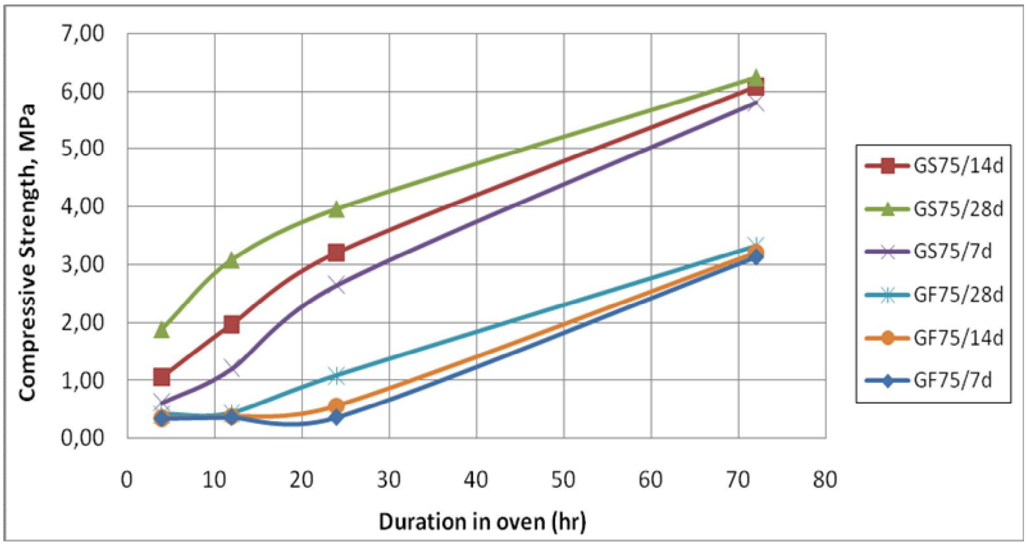

Figure 5.23 “Compressive Strength of GF75 and GS75 Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Curing Times

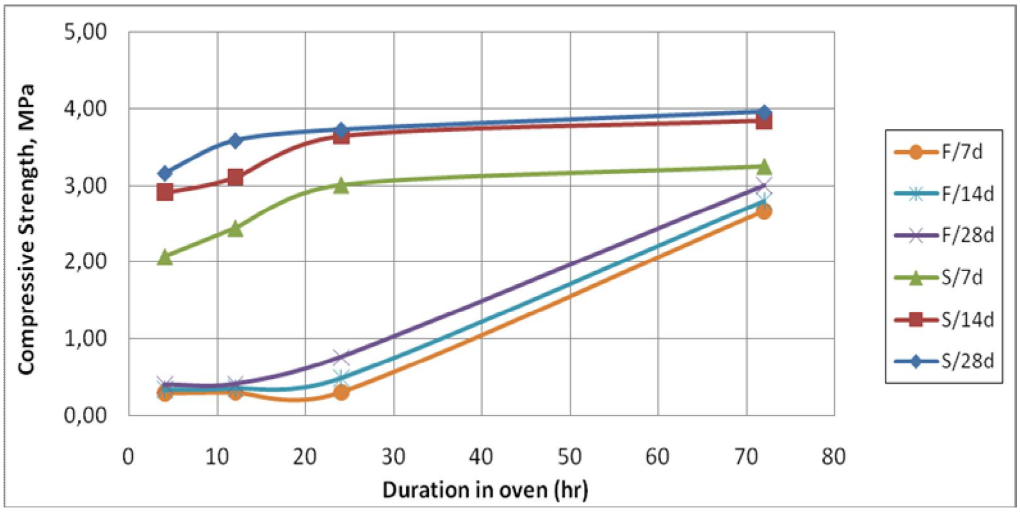

Figure 5.24 “Compressive Strength of F and S Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Curing Times

On the other hand, for the mixtures cured in an 80 ^{0}C oven for a while, then cured in water at 20 ^{0}C; as can be seen from Figure 5.25 to 5.30,

- In general, the compressive strengths of the mixtures at 7-, 14-, and 28-day increase with the extension of the curing duration in the oven.

- With the extension of the curing days it can be seen increases in strength values as an evidence of the hydration.

- For the mixtures containing slag as a pozzolanic material; it can be seen

  a) From Figure 5.25, the strength values at 14- and 28-day are close to each other and with the extension of curing durations in the oven, the strength values at 14- and 28-day are closer to each other but the strength difference between them and the strength values at 7-day increases;

  b) From Figure 5.26 and 5.29, the differences between the strength values at 7-, 14-, and 28-day are constant with the extension of curing durations in the oven;

  c) From Figure 5.27, with the extension of curing durations in the oven, the difference between the strength values at 14- and 28-day is constant and the strength difference between them and the strength values at 7-day increases;

  d) From Figure 5.28, with the extension of curing durations in the oven, the difference between the strength values at 7- and 14-day is constant and the strength difference between them and the strength values at 28-day increases;

e) From Figure 5.30, the strength values at 14- and 28-day are closer to each other but the strength difference between them and the strength values at 7-day is constant.

- For the mixtures containing fly ash as a pozzolanic material; in general the strength values for all curing days are very close to each other up to nearly 12 hours in oven then the strength differences occur between them but these differences decrease or become constant with the extension of the curing duration in the oven.

- It can be seen that the compressive strengths of the mixtures containing slag are higher than those of the mixtures containing fly ash for all curing days in Figure 5.25 and 5.26, for 14 and 28 curing days (for 7 days they are higher up to 65 hours curing in the oven) in Figure 5.27, for 28 curing days (at 7- and 14-days they are higher up to 68 hours and 62 hours curing in the oven, respectively) in Figure 5.28. As can be seen from Figure 5.29, on the other hand, the compressive strengths of the mixtures containing fly ash are higher than those of the mixtures containing slag only for 28 curing days and for 68-72 hours curing in the oven, also from Figure 5.30, the compressive strengths of the mixtures containing fly ash are higher than those of the mixtures containing slag for 64-72 hours curing in the oven.

This may be an indication of the mixtures containing fly ash compensating the earlier activation of the mixtures containing slag with the increasing of the curing duration and duration in the oven at 80 ^{0}C.

It can be said that on the whole, the activation of the slag is slightly higher than that of fly ash for the mixtures cured in oven at 80 ^{0}C for a time then cured in water at 20 ^{0}C.

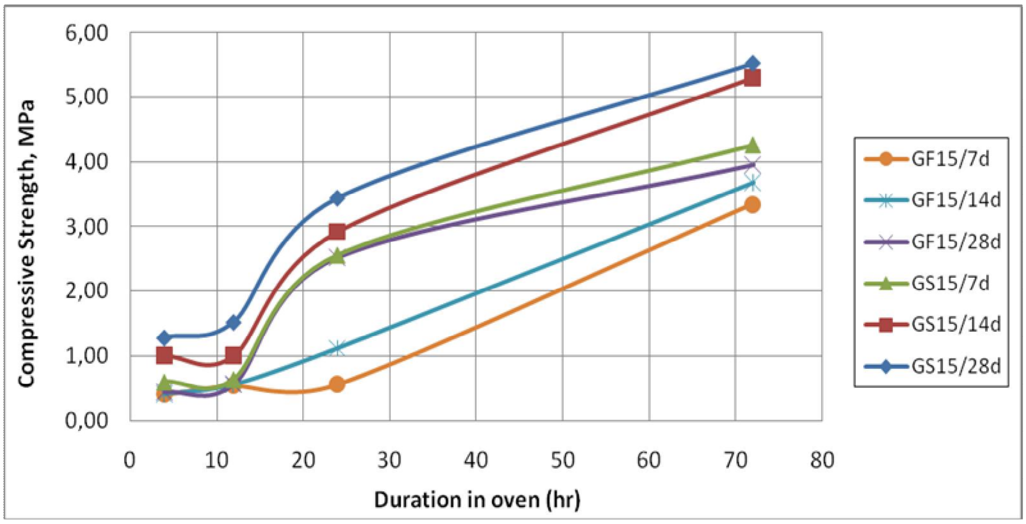

Figure 5.25 “Compressive Strength of GF15 and GS15 Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Curing Times

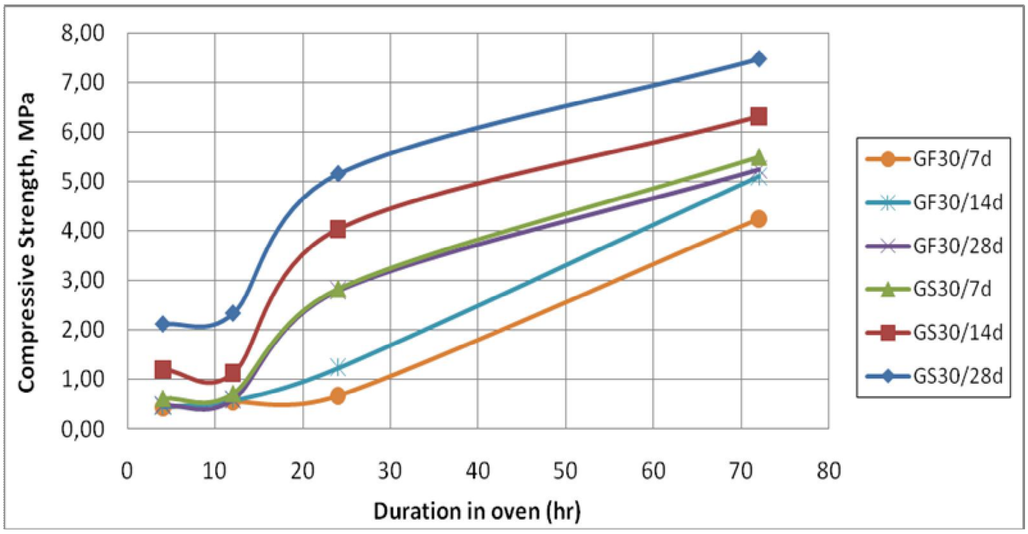

Figure 5.26 “Compressive Strength of GF30 and GS30 Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Curing Times

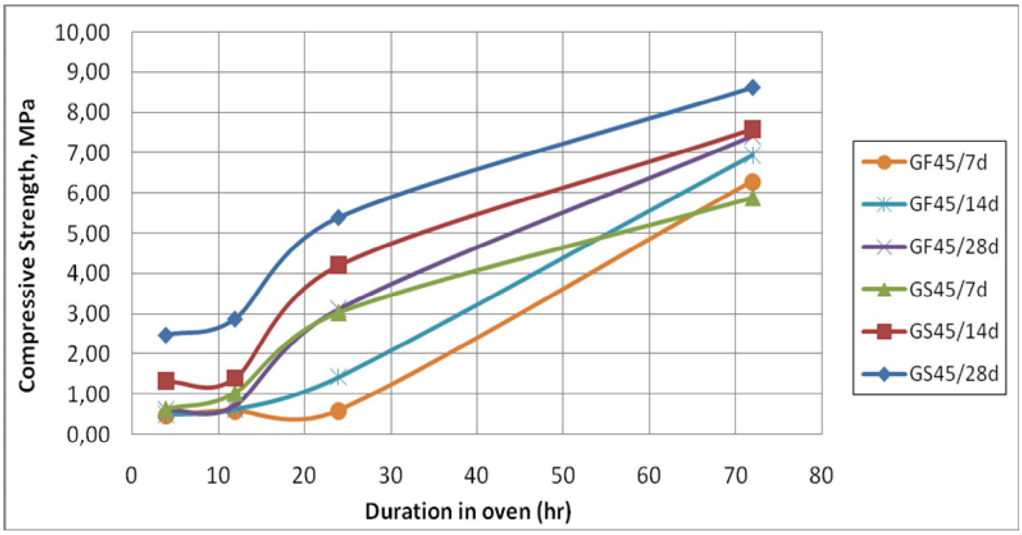

Figure 5.27 "Compressive Strength of GF45 and GS45 Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Curing Times

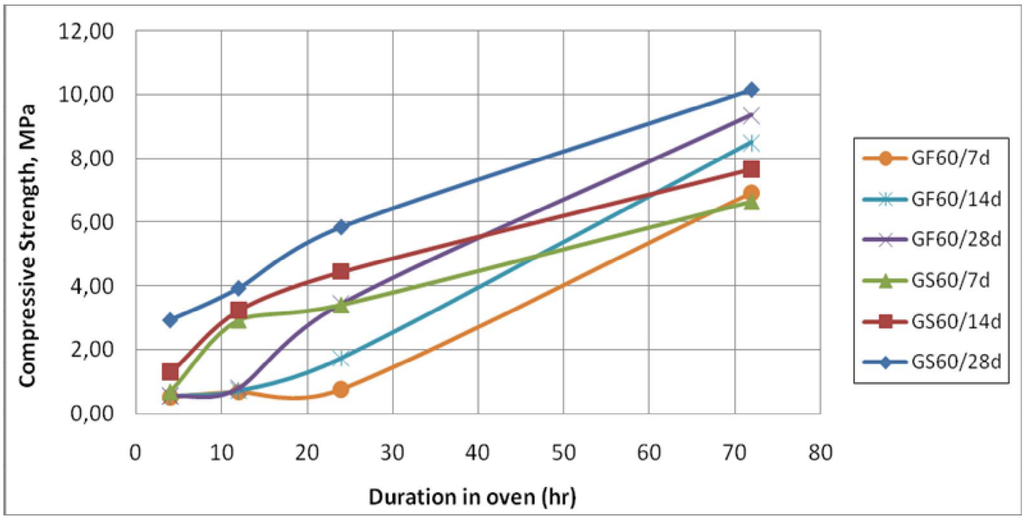

Figure 5.28 "Compressive Strength of GF60 and GS60 Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Curing Times

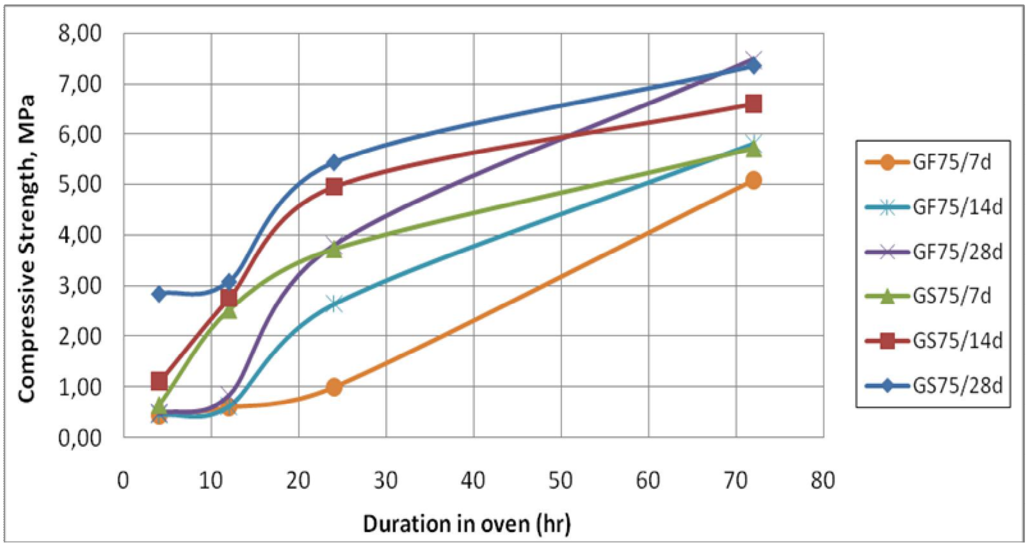

Figure 5.29 "Compressive Strength of GF75 and GS75 Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Curing Times

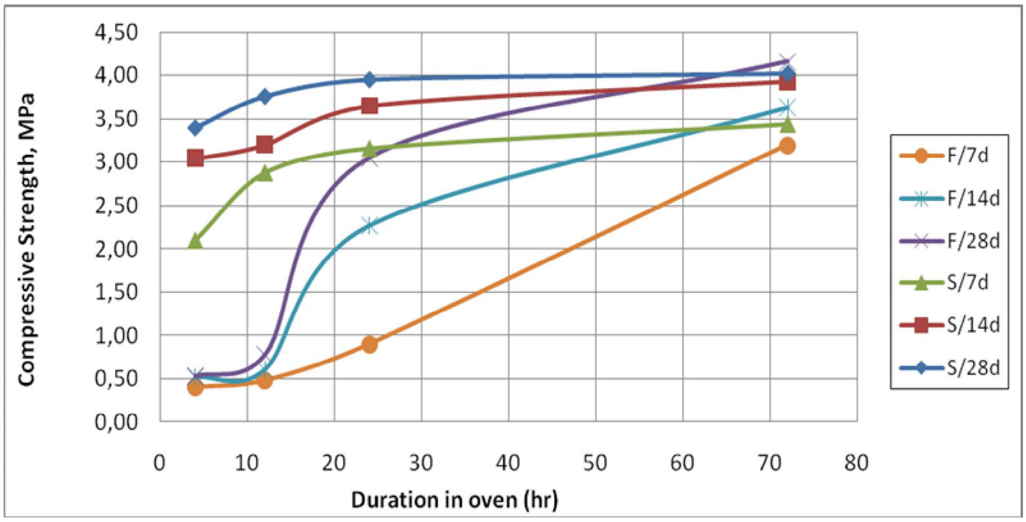

Figure 5.30 "Compressive Strength of F and S Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Curing Times

5.4. Evaluation of the Relationship between Pozzolanic Ratio and Curing Duration at Elevated Temperature According to Performances of the Mixtures

In this part of the study, the effects of elevated temperature curing and the amount of pozzolans on the performances of the mixtures having the same type of pozzolan were investigated. In this way, the comparison of the mixtures having the same type of pozzolan but in different amounts under high temperature curing was able to be made.

The relations between the compressive strength of the mixtures and duration in oven can be seen in graphical form in the Appendix A. (Figure A.55 to A.66)

It can be said that nearly for all mixtures cured in oven at 50 ^{0}C and 80 ^{0}C for a while, then cured in water at 20 ^{0}C; the compressive strength values for all curing days increase as the curing duration in the oven increases.

As can be seen from the figures in the Appendix A, from Figure A.55 to Figure A.60, for the mixtures cured in at 50 ^{0}C oven for a while, then cured in water at 20 ^{0}C;

- For the mixtures containing fly ash as a pozzolanic material, in general, GF75 and GF60 have the highest compressive strength values and GF15 has the lowest ones for all curing days.
- For the mixtures containing slag as a pozzolanic material; for 7 and 14 days, the highest compressive strength values belong to S up to 30 hours after that they belong to generally GS60 and GS75; on the other hand, for 28 days, they belong to S up to 10 hours after that they belong to GS60 according to curing durations in oven.

- For the mixtures containing slag as a pozzolanic material; the lowest compressive strength values belong to GS15 up to 51 hours for 7 days; up to 48 hours for 14 and 28 days, and after these hours, they belong to S according to curing durations in oven.

- It can be concluded that both fly ash and slag have been activated by adding gypsum and hydrated lime for the mixtures cured in a 50 ^{0}C oven for a while, then cured in water at 20 ^{0}C.

As can be seen from the figures in Appendix, from Figure A.61 to Figure A.66, for the mixtures cured in an 80 ^{0}C oven for a while, then cured in water at 20 ^{0}C;

- For the mixtures containing fly ash as a pozzolanic material, in general, GF75, GF60 have the highest compressive strength values and GF15 and F has the lowest ones for different curing durations in oven for all curing days.

- For the mixtures containing slag as a pozzolanic material; the highest compressive strength values belong to S up to 11 hours after that they belong to generally GS60 and GS75 for all curing days according to curing durations in oven.

- For the mixtures containing slag as a pozzolanic material; the lowest compressive strength values belong to GS15 up to 40 hours for 7 and 14 days; up to 32 hours for 28 days, and after these hours, they belong to S according to curing durations in oven.

- It can be concluded that both fly ash and slag have been activated by adding gypsum and hydrated lime for the mixtures cured in an 80 ^{0}C oven for a while, then cured in water at 20 ^{0}C.

5.5. Evaluation of the Effect of Curing Temperatures on the Performances of the Mixtures According to Curing Duration in the Oven

The effects of elevated temperature curing on the performances of the mixtures having the same amount and type of pozzolan were investigated. In this way, the comparison of the behavior of the mixtures having the same amount and type of pozzolan under different curing temperatures was able to be made.

The relations between the compressive strength of the mixtures and curing duration in oven can be seen in graphical form in the Appendix A. (Figure A.67 to Figure A.102) For all mixtures, for all curing temperatures and durations in oven, the lowest compressive strength values belong to the mixtures only cured in water at 20^0C. This is an indication of the positive effect of the elevated temperature curing on the activation of the pozzolans.

As can be seen from the figures in the Appendix A, from Figure A.67 to Figure A.84, for the mixtures containing fly ash as a pozzolanic material and cured in oven for a while, then cured in water at 20 ^{0}C;

- In general terms, for the mixtures cured in an 80 ^{0}C oven, the compressive strength values of the mixtures for all curing days slightly increase or decrease for some mixtures up to 10 hours or 24 hours then increase as the curing duration in the oven increases, for some others, they directly increase as the curing duration in the oven increases.

  On the other hand, for the mixtures cured in a 50 ^{0}C oven, the compressive strength values of the mixtures for all curing days become nearly constant up to a point between 10 hours to 24 hours then increase as the curing duration in the oven increases.

- The highest compressive strength values belong to the mixtures cured in an 80 ^{0}C oven. The differences in strength values for the mixtures at 20 ^{0}C, 50 ^{0}C and 80 ^{0}C except for F increase as the curing duration in the oven increases.

As can be seen from the figures in the Appendix A, from Figure A.85 to Figure A.102, for the mixtures containing slag as a pozzolanic material and cured in oven for a while, then cured in water at 20 ^{0}C;

- In general terms; for the mixtures cured in an 80 ^{0}C oven, for all curing days; the compressive strength values of GS15 and GS30 slightly increase or decrease up to 12 hours then increase as the curing duration in the oven increases, for others, the compressive strength values directly increase as the curing duration in the oven increases.

  For the mixtures cured in a 50 ^{0}C oven, for all curing days; the compressive strength values of GS15 and GS30 slightly increase or decrease up to a point between 10 hours to 24 hours then increase as the curing duration in the oven increases, for others, the compressive strength values directly increase as the curing duration in the oven increases.

  Generally, the highest compressive strength values belong to the mixtures cured in an 80 ^{0}C oven. On the other hand, the differences in strength values of the mixtures cured in oven at 50 ^{0}C and 80 ^{0}C decrease or become nearly constant as the curing duration in the oven increases. The mixtures cured at 50 ^{0}C compensate the earlier activation of the mixtures cured at 80 ^{0}C with the curing duration at elevated temperature.

As a result, for all mixtures, the highest compressive strength values belong to the mixes cured in oven at 80 ^{0}C and the lowest ones belong to the mixes only cured at 20 ^{0}C in water. When the temperature of curing is as low as 20 ^{0}C the reactions causing hydration products are relatively slow especially for the mixtures containing fly ash as a pozzolanic material and hardened mixtures are not so strong to the action of water. On the other hand, with thermal treatment at higher temperatures (50 ^{o}C - 80 ^{o}C) the mixtures are stronger and sound even in the presence of water in service. The highly increased reaction rate causing the formation of calcium-silica-hydrate gels and well-crystallized ettringite fibers, favoured by the higher temperature of the curing treatment, are considered to be responsible for the better mechanical performances.

5.6. Evaluation of the Relationships of the Strength, Porosity and Water Absorption Capacity of the Mixtures Subjected to Different Curing Regimes

In this part of the study, the strength, porosity and water absorption capacity relationships of some mixtures cured in different conditions were wanted to be determined. One of the indications of the improved gypsum properties by pozzolanic material incorporation and elevated temperature curing is that the mixtures having gypsum, pozzolan and hydrated lime have higher strength and also lower water absorption capacity with lower porosity. Lower porosity is also one of the effects of the sulfate activation mechanism i.e. activation of pozzolans with sulfates. For these purposes, porosity and water absorption capacity values of some mixtures were determined. After that, relationships between physical and mechanical properties of the mixtures were set up.

Table 5.19 Physical Properties of the Mixtures

Type of Mixtures/ Curing Condition/ Curing Day	Water Absorption Capacity (%)	Porosity (%)
G-80^{0}C/72h/28d**	29,98	35,84
F-80^{0}C/72h/28d	20,73	27,58
S-80^{0}C/72h/28d	20,78	27,63
GF45-80^{0}C/72h/28d	15,14	21,25
GF75-80^{0}C/72h/28d	14,68	20,73
GS45-80^{0}C/72h/28d	11,96	17,50
GS60-80^{0}C/72h/28d	9,63	14,54
GF30-80^{0}C/72h/14d	19,64	25,07
GF75-80^{0}C/72h/14d	18,79	24,19
GS30-80^{0}C/72h/14d	18,48	23,88
GS75-80^{0}C/72h/14d	17,60	22,98
GF30-80^{0}C/72h/7d	20,63	27,47
GF75-80^{0}C/72h/7d	19,73	25,17
GS30-80^{0}C/72h/7d	19,22	24,64
GS75-80^{0}C/72h/7d	19,05	24,46
GF45-50^{0}C/72h/28d	22,62	29,35

Table 5.19 (continued)

GF60-50^{0}C/72h/28d	22,55	28,28
GS45-50^{0}C/72h/28d	18,91	24,32
GS60-50^{0}C/72h/28d	17,92	23,31
GF30-20^{0}C/28d	29,71	35,18
GF75-20^{0}C/28d	30,47	35,34
GS30-20^{0}C/28d	27,17	33,16
GS75-20^{0}C/28d	25,02	32,40

*SSD: Saturated Surface Dry

**For example, G-80^{0}C/72h/28d means G type of mixture cured at 80^{0}C for 72hours in oven then cured in water at 20^{0}C for 28 days

Table 5.19 shows the physical properties of the mixtures. Figure 5.31 and 5.32 shows the directly inverse proportion between the compressive strength of the mixtures and the porosity and water absorption capacity of them. As can be seen from these table and figures, the porosity values of the mixtures having pozzolans, hydrated lime and gypsum together are much lower than that of gypsum paste and also lower than that of F and S type mixtures especially for the same curing conditions. It can be said that the addition of pozzolans and hydrated lime into gypsum with elevated temperature curing changed the behavior of the mixture. The mixtures although having gypsum as a major constituent had much lower porosity and water absorption values under water compared to those of gypsum paste. Lower porosity and water absorption capacity of the mixtures is a clear indication of the improved water resistance of gypsum and the enhanced activation of the pozzolans with hydrated lime and gypsum by sulfate activation mechanism.

It can be said that the porosity and water absorption capacity values of the mixtures decrease as the curing temperature and duration in oven, and also hydration period increase. The significant reduction in porosity and water absorption capacity of the mixtures cured at elevated temperatures may be due to filling of pores in the hardened matrix by the enhanced quantities of ettringite and calcium-silicate-hydrate gels. This will cause better water resistance of the mixtures cured at elevated temperatures and the structure becomes more dense attributing high strength. Similarly, as the hydration period increases, the mixtures produce more hydration products and the cohesive force of interface is enhanced as well as the porosity of the mixtures is being improved.

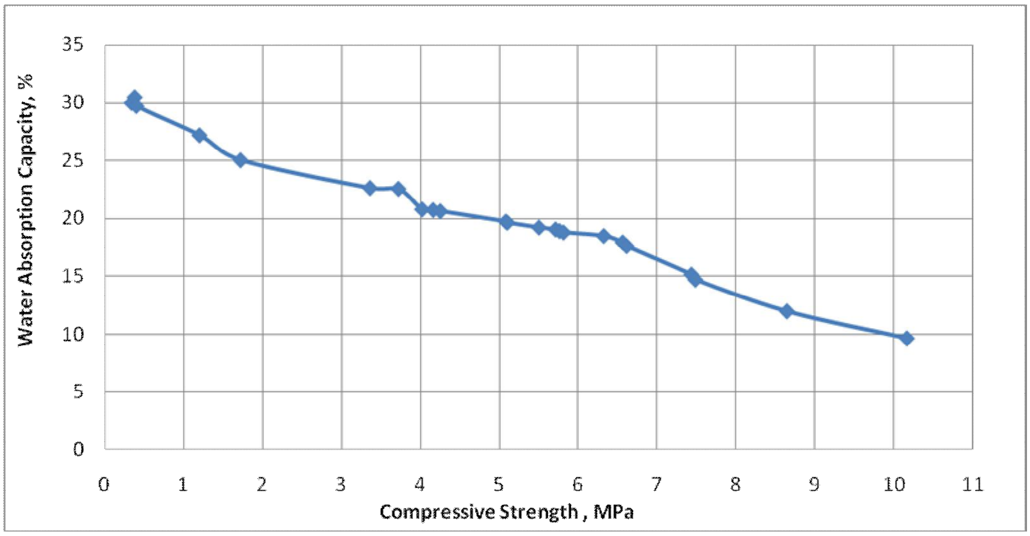

Figure 5.31 Compressive Strength vs. Water Absorption Capacity of the Mixtures

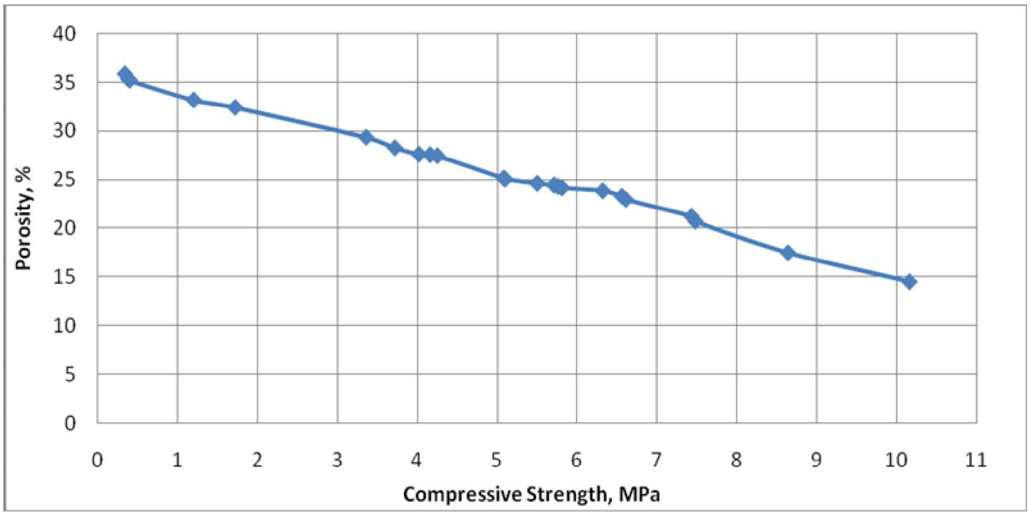

Figure 5.32 Compressive Strength vs. Porosity of the Mixtures

5.7. Evaluation of the XRD Analysis of the Mixtures

In this part of the study, in order to examine crystalline hydration products qualitatively, to observe some possible similarities and differences in samples and to find out the reasons behind the behavior of the mixtures, XRD analysis were applied to some samples.

Therefore, microstructures of the some mixtures cured at 80 ^{0}C for 72 hours in oven then cured in water at 20 ^{0}C for 28 days were investigated by XRD analysis. The results can be seen from Figure 5.33 to 5.38.

As can be seen from 5.33 to 5.35 and 5.36 to 5.39, the main difference of the mixtures containing pozzolans, hydrated lime and gypsum is the ettringite formation as a hydration product. This can be also one of the effects of the sulfate activation mechanism of the pozzolans. The extent of filling of the pore spaces with hydration products and also strength values are higher for these mixtures. With the addition of gypsum into pozzolans and hydrated lime, gypsum combines with alumina contributed by the pozzolans in the presence of hydrated lime to form ettringite ($C_6A\bar{S}_3H_{32}$); also hydrated lime interacts with silica content of pozzolans to form calcium-silica-hydrate gels (C-S-H). SO_4^{-2} ions provided with gypsum penetrate into phase of the pozzolans, disturb balance of the system and improve the reactivity of pozzolans.

The peaks of the ettringite compounds can also be meaningful. If it is correlated with the amount of the compound, for the same type of pozzolans, it can be said that there is a direct proportion between the peaks of ettringite compounds of the mixtures and the strength values of them. Large amounts of ettringite produced upon hydration may result in the high strength.

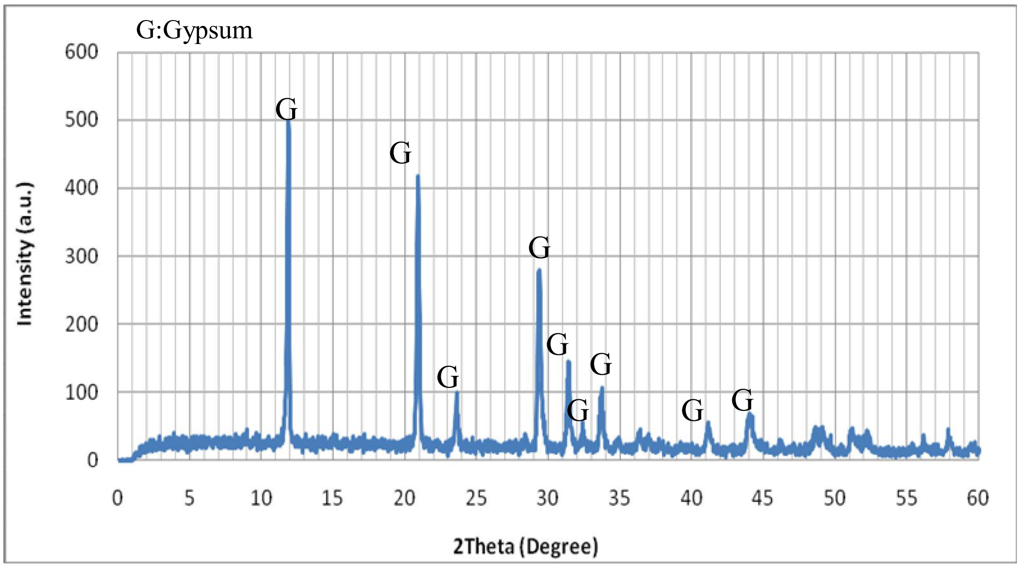

Figure 5.33 XRD Analysis of G Type Mixture

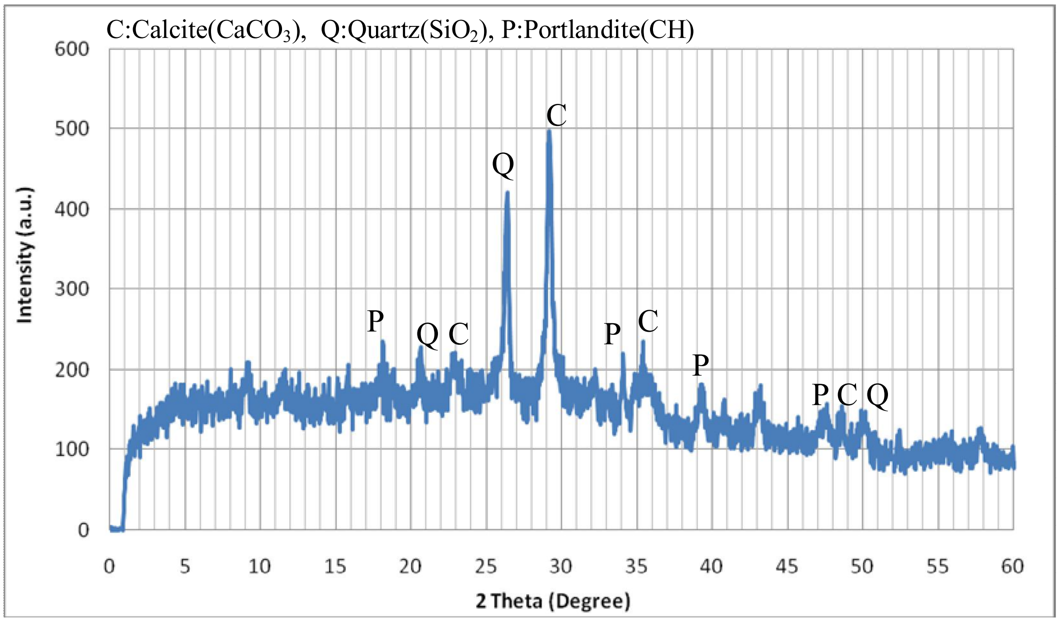

Figure 5.34 XRD Analysis of F Type Mixture

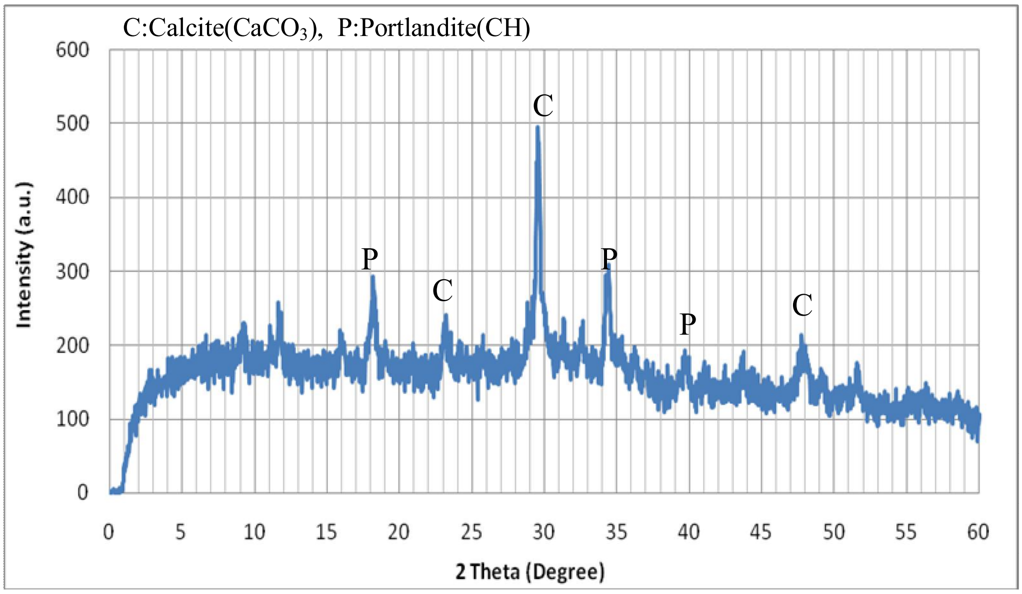

Figure 5.35 XRD Analysis of S Type Mixture

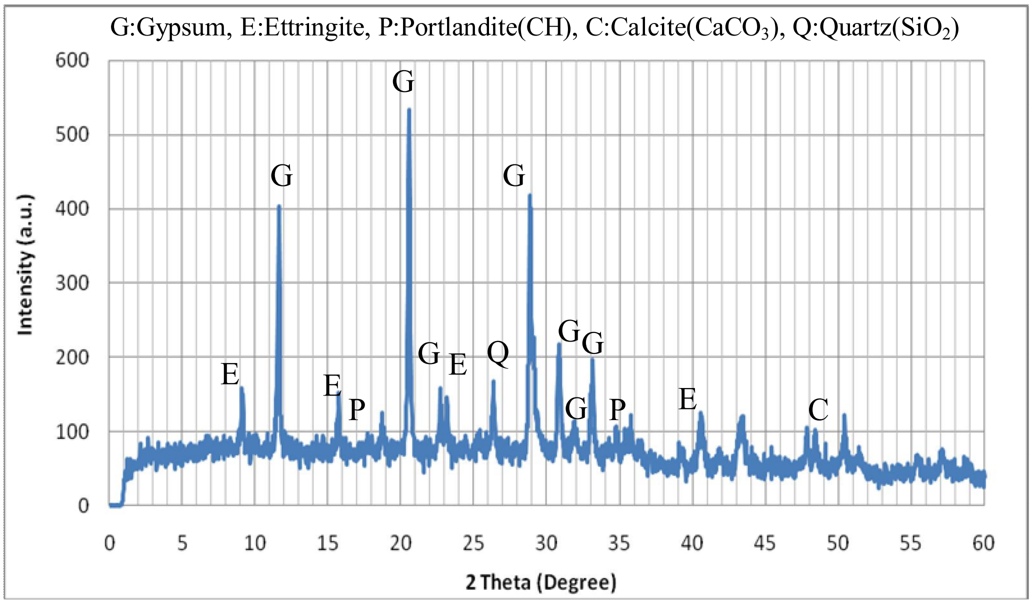

Figure 5.36 XRD Analysis of GF45 Type Mixture

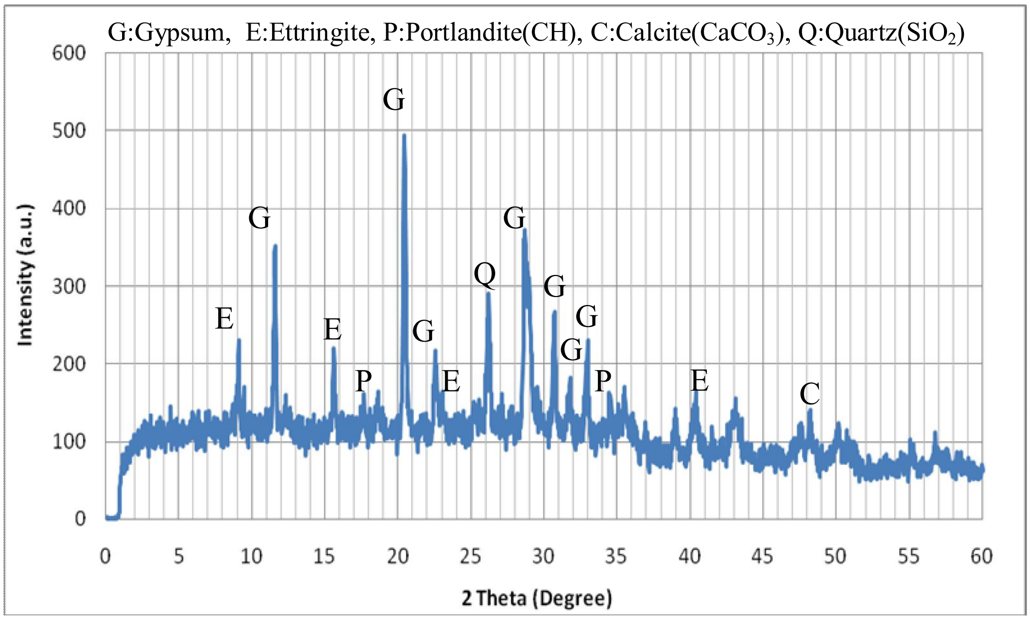

Figure 5.37 XRD Analysis of GF60 Type Mixture

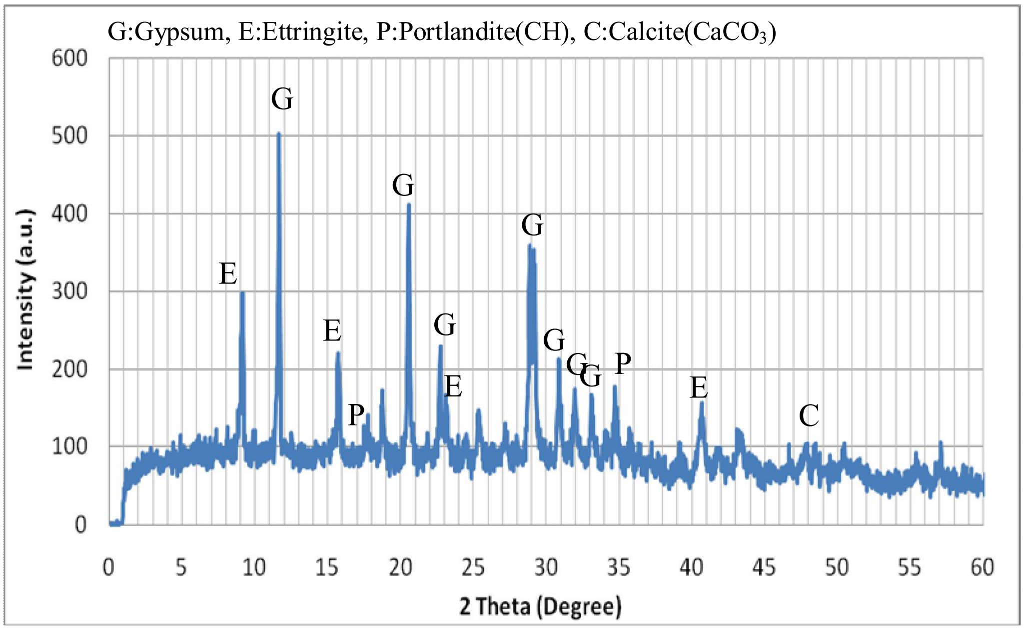

Figure 5.38 XRD Analysis of GS45 Type Mixture

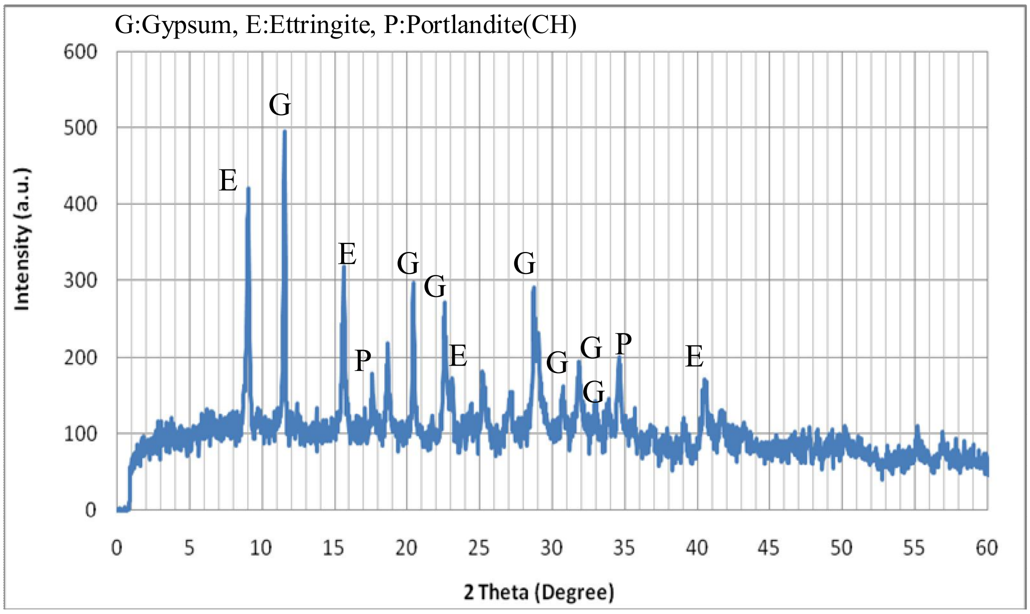

Figure 5.39 XRD Analysis of GS60 Type Mixture

CHAPTER 6

CONCLUSIONS

1. The strength and water resistance of natural gypsum paste are improved substantially by incorporation of pozzolans and hydrated lime especially at elevated temperature curing. ”natural gypsum + pozzolan + lime” mixtures have higher strengths and lower porosities as compared to those mixtures consisted only “pozzolan + lime”.

2. Optimum contents of the materials used in the mixtures are provided approximately as “33.5% natural gypsum + 47.5% fly ash + 19% hydrated lime” or “40.5% natural gypsum + 42.5% slag + 17% hydrated lime”.

3. Increase in strength and decrease in porosity of the ”natural gypsum + pozzolan + lime” mixtures are affected by the type of pozzolan used and the extent of occurrence of pozzolanic activity.

   a) Pozzolanic activity of both fly ash and blast-furnace slag incorporated mixtures increases with the application of elevated temperature especially for 80 ^{0}C and increases in age. However, the blast-furnace slag incorporating mixtures show slightly better performance as compared to those fly ash incorporated ones. This is due to the following fact:

   Actually, the activation mechanism of hydrated lime and blast-furnace slag is similar to that of hydrated lime and fly ash. On the other hand, there are some differences because of high self-cementitious nature of the slag. Slag contains a high amount of CaO as active constituent and more of it is readily dissolved into solution than in the mixtures containing hydrated lime and fly ash when water is added. Thus hydration products form quickly in the mixtures containing hydrated lime and slag. The self-cementitious property of slag densifies and strengthens the pastes. The presence of natural gypsum in the mixture containing hydrated lime and slag accelerates the dissolution of slag and leads to formation of more hydration products.

b) Increase in strength and decrease in porosity is related not only to the progress of pozzolanic reaction but also to the development of hydration products such as ettringite and some calcium-silicate-hydrate gels. These hydration products that fill the pores in the matrix also enhance the cohesive forces of interfaces causing the structure to become denser. The lower total pore content thus obtained leads to higher strength and higher water resistance of the mix.

4. Increase in strength and decrease in porosity due to the development of pozzolanic activity and formation of hydration products might enable natural gypsum pastes to be able to be used in outdoor applications in the building industry.

CHAPTER 7

RECOMMENDATIONS

Following items can be recommended for further researches:

- In this study, Type-F fly ash according to ASTM C 618 and ground granulated blast-furnace slag were incorporated into natural gypsum pastes as pozzolanic materials. Type-C fly ash according to ASTM C 618 or high-lime fly ash having a CaO content higher than 10% can be incorporated into gypsum pastes in further investigations. The self-cementitious property of the C-type fly ash may be effective on the properties of the natural gypsum paste like the ground granulated blast-furnace slag.

- The incorporation of very finely divided pozzolans such as silica fume which possesses excellent pozzolanic properties due to high content of non-crystalline SiO_2 might cause acceleration in the occurrence of pozzolanic reactions. Thus higher strength and lower porosity might be obtained in early ages. The optimum fineness of these pozzolanic materials to improve the properties of the natural gypsum pastes should be determined by further investigations.

- In this investigation some of the samples were subjected to elevated temperatures in an oven for various durations, taken out and then placed in water and kept at 20 ± 2°C condition until the time of testing. The effect of steam curing may be investigated on the properties of the mixtures in further studies. Steam curing method will enable pozzolan and hydrated lime incorporated gypsum mixtures to possess increased hydration rate with high early strength. On the other hand, high temperature and humidity provided by steam curing can affect gypsum in the mixtures adversely by increasing their solubilities, thereby losing rigidity of the mixtures.

Also, after the samples subjected to elevated temperatures and taken out from oven may be placed in water and kept at lower temperatures such as at 0±5°C.The effect of low temperatures on the properties of the mixtures can be investigated in further studies. New hydration products like thaumasite similar to ettringite may be formed although the reactions might be slower due to low curing temperature.

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APPENDIX A

Table A.1 Compressive Strength Test Results of the Mixes Cured at 20 °C

	Compressive Strength, MPa		
Samples	7 days	14 days	28 days
G	0.27	0.26	0.27
GF15	0.30	0.32	0.35
GF30	0.35	0.38	0.40
GF45	0.35	0.38	0.40
GF60	0.37	0.40	0.42
GF75	0.34	0.35	0.38
F	0.30	0.32	0.33
GS15	0.54	0.80	0.84
GS30	0.58	0.92	1.20
GS45	0.60	1.00	1.66
GS60	0.62	1.05	1.80
GS75	0.59	1.03	1.72
S	2.05	2.75	3.10

Table A.2 Compressive Strength Test Results of the Mixes Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C

	Compressive Strength, MPa		
Samples	7 days	14 days	28 days
G	0.28	0.27	0.27
GF15	0.30	0.31	0.36
GF30	0.35	0.36	0.38
GF45	0.35	0.38	0.40
GF60	0.37	0.39	0.44
GF75	0.34	0.35	0.41
F	0.29	0.33	0.40
GS15	0.52	0.92	1.12
GS30	0.56	1.12	1.58
GS45	0.60	1.20	1.80
GS60	0.64	1.23	1.98
GS75	0.61	1.05	1.88
S	2.07	2.90	3.15

Table A.3 Compressive Strength Test Results of the Mixes Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C

Samples	Compressive Strength, MPa		
	7 days	14 days	28 days
G	0.28	0.27	0.27
GF15	0.40	0.41	0.44
GF30	0.44	0.45	0.48
GF45	0.48	0.50	0.60
GF60	0.52	0.53	0.54
GF75	0.44	0.45	0.48
F	0.40	0.52	0.53
GS15	0.60	1.00	1.28
GS30	0.62	1.20	2.12
GS45	0.64	1.32	2.48
GS60	0.68	1.28	2.92
GS75	0.64	1.10	2.84
S	2.10	3.04	3.40

Table A.4 Compressive Strength Test Results of the Mixes Cured for 12 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C

	Compressive Strength, MPa		
Samples	7 days	14 days	28 days
G	0.28	0.27	0.27
GF15	0.33	0.34	0.36
GF30	0.35	0.36	0.38
GF45	0.35	0.38	0.40
GF60	0.38	0.41	0.45
GF75	0.36	0.38	0.43
F	0.30	0.35	0.41
GS15	0.72	1.00	1.40
GS30	0.76	1.16	1.66
GS45	0.88	1.40	2.08
GS60	1.00	2.12	3.70
GS75	1.20	1.96	3.08
S	2.44	3.10	3.58

Table A.5 Compressive Strength Test Results of the Mixes Cured for 12 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C

Samples	Compressive Strength, MPa 7 days	14 days	28 days
G	0.32	0.35	0.35
GF15	0.54	0.56	0.56
GF30	0.56	0.58	0.60
GF45	0.60	0.64	0.72
GF60	0.68	0.70	0.80
GF75	0.60	0.62	0.84
F	0.48	0.61	0.78
GS15	0.64	1.00	1.52
GS30	0.72	1.12	2.34
GS45	1.04	1.40	2.88
GS60	2.92	3.24	3.92
GS75	2.52	2.76	3.08
S	2.88	3.20	3.76

Table A.6 Compressive Strength Test Results of the Mixes Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20^{0}C

	Compressive Strength, MPa		
Samples	7 days	14 days	28 days
G	0.28	0.27	0.27
GF15	0.33	0.48	0.64
GF30	0.35	0.52	0.72
GF45	0.35	0.56	0.96
GF60	0.38	0.60	1.04
GF75	0.36	0.56	1.08
F	0.30	0.48	0.76
GS15	0.75	2.24	2.40
GS30	1.00	2.36	3.04
GS45	1.20	2.48	3.28
GS60	1.32	3.28	4.08
GS75	2.64	3.20	3.96
S	3.00	3.64	3.72

Table A.7 Compressive Strength Test Results of the Mixes Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C

Samples	Compressive Strength, MPa 7 days	 14 days	 28 days
G	0.35	0.32	0.35
GF15	0.56	1.12	2.52
GF30	0.68	1.24	2.80
GF45	0.60	1.44	3.12
GF60	0.76	1.72	3.44
GF75	1.00	2.64	3.80
F	0.90	2.27	3.05
GS15	2.56	2.92	3.44
GS30	2.84	4.04	5.16
GS45	3.04	4.20	5.40
GS60	3.40	4.44	5.84
GS75	3.72	4.96	5.44
S	3.16	3.65	3.95

Table A.8 Compressive Strength Test Results of the Mixes Cured for 72 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C

Samples	Compressive Strength, MPa		
	7 days	14 days	28 days
G	0.35	0.35	0.34
GF15	1.00	1.20	1.40
GF30	2.48	2.88	2.96
GF45	2.88	3.04	3.36
GF60	3.00	3.38	3.72
GF75	3.12	3.20	3.32
F	2.96	3.25	3.60
GS15	4.92	5.24	5.33
GS30	5.20	5.32	5.58
GS45	5.56	5.68	5.76
GS60	6.28	6.32	6.56
GS75	5.80	6.08	6.24
S	3.24	3.84	3.95

Table A.9 Compressive Strength Test Results of the Mixes Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C

	Compressive Strength, MPa		
Samples	7 days	14 days	28 days
G	0.37	0.35	0.34
GF15	3.35	3.68	3.95
GF30	4.25	5.10	5.24
GF45	6.30	6.96	7.43
GF60	6.93	8.51	9.36
GF75	5.08	5.81	7.48
F	3.20	3.63	4.16
GS15	4.26	5.30	5.52
GS30	5.50	6.32	7.48
GS45	5.89	7.59	8.64
GS60	6.64	7.68	10.16
GS75	5.71	6.61	7.36
S	3.44	3.93	4.02

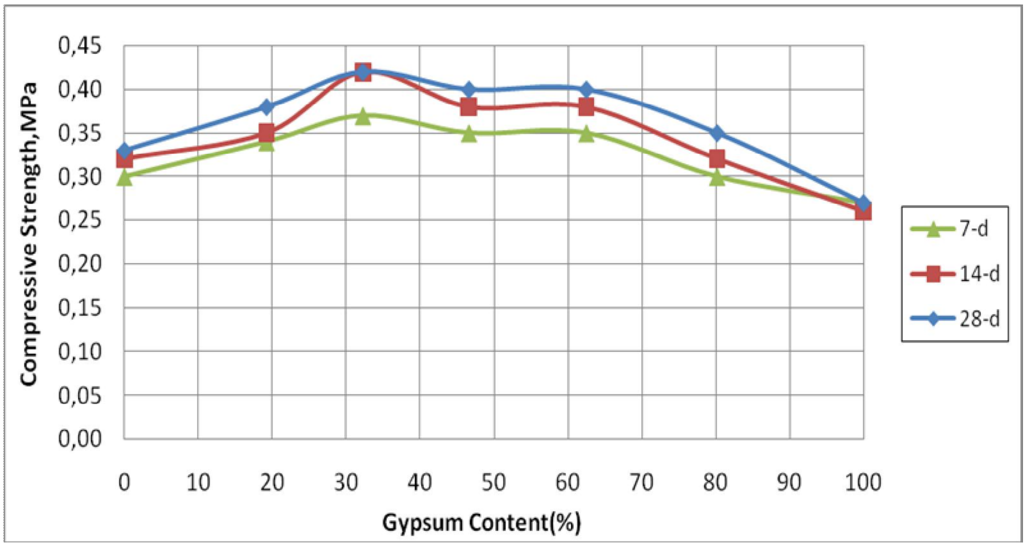

Figure A.1 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured at 20 ^{0}C vs. Gypsum Content” Relationships for Different Curing Times

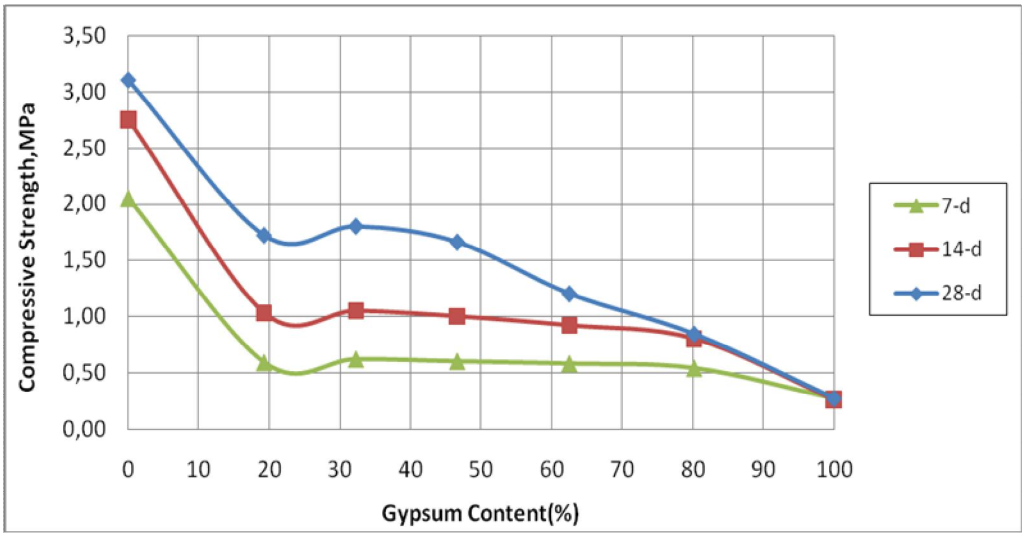

Figure A.2 “Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured at 20 ^{0}C vs. Gypsum Content” Relationships for Different Curing Times

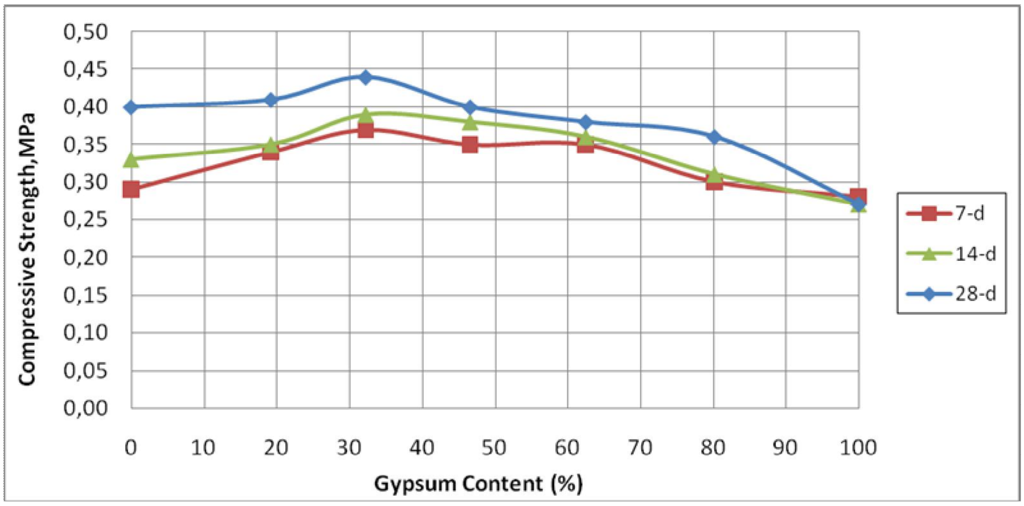

Figure A.3 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content” Relationships for Different Curing Times

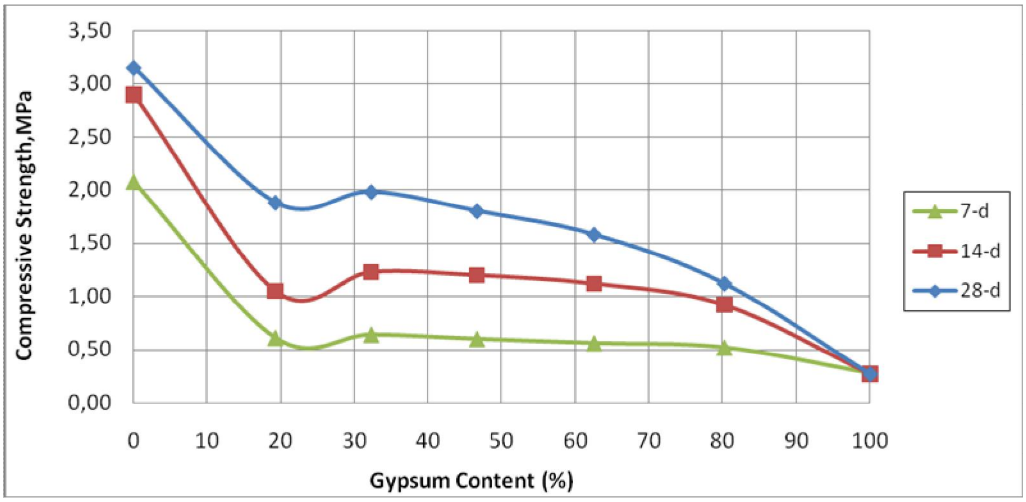

Figure A.4 “Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content” Relationships for Different Curing Times

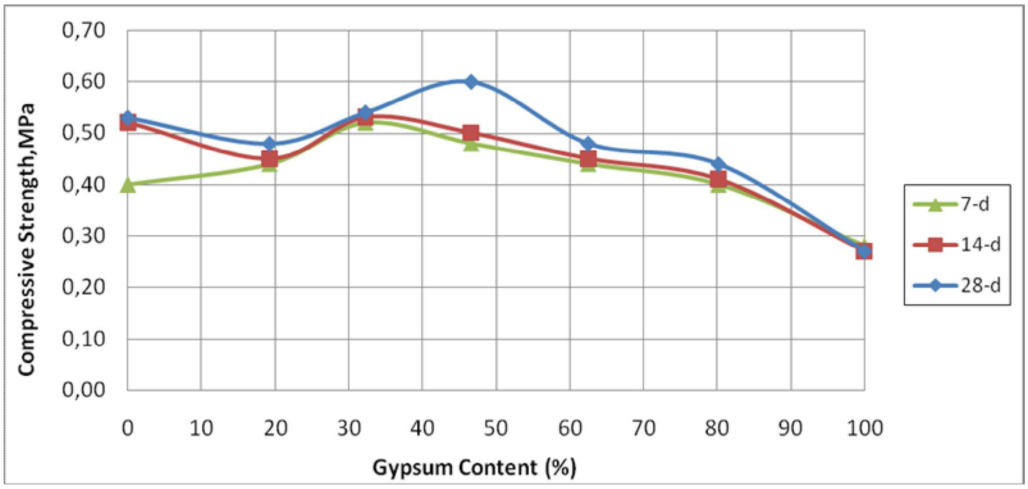

Figure A.5 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content” Relationships for Different Curing Times

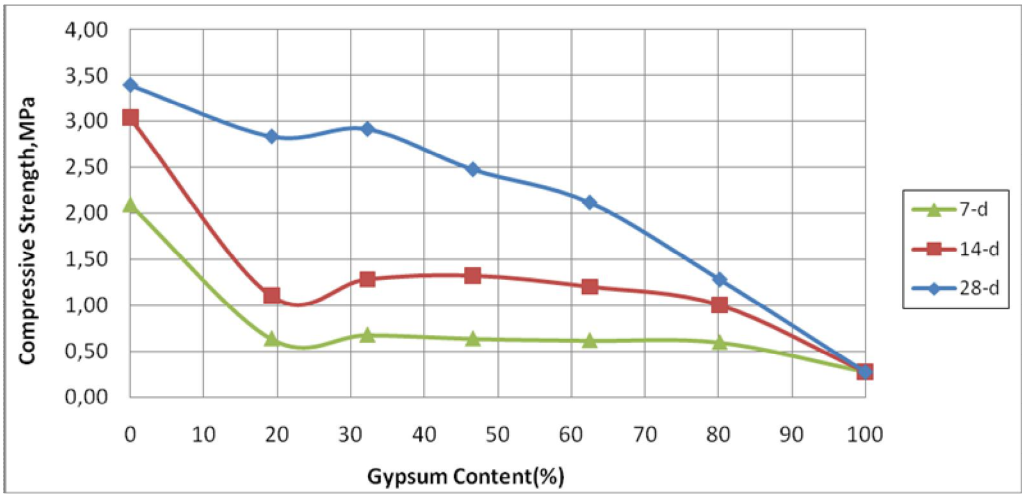

Figure A.6 “Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content” Relationships for Different Curing Times

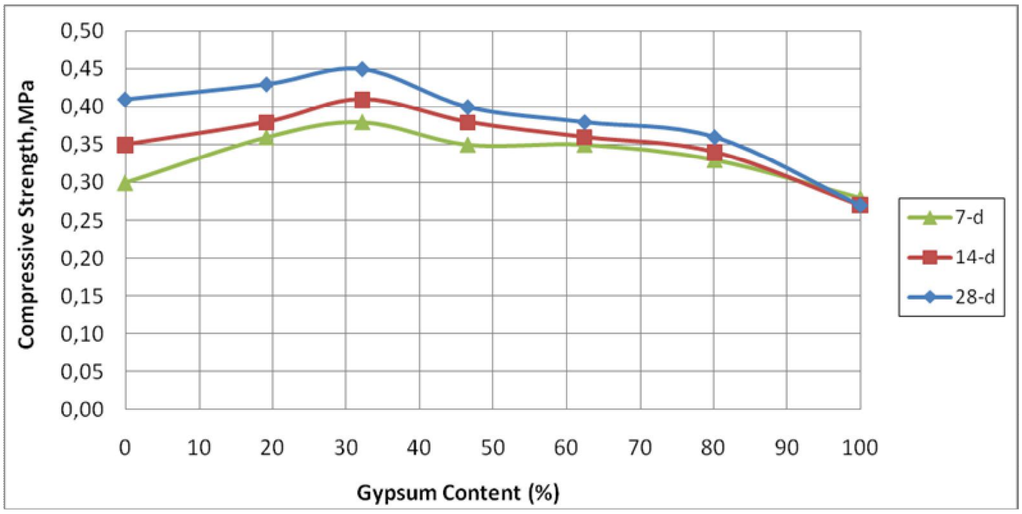

Figure A.7 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured for 12 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

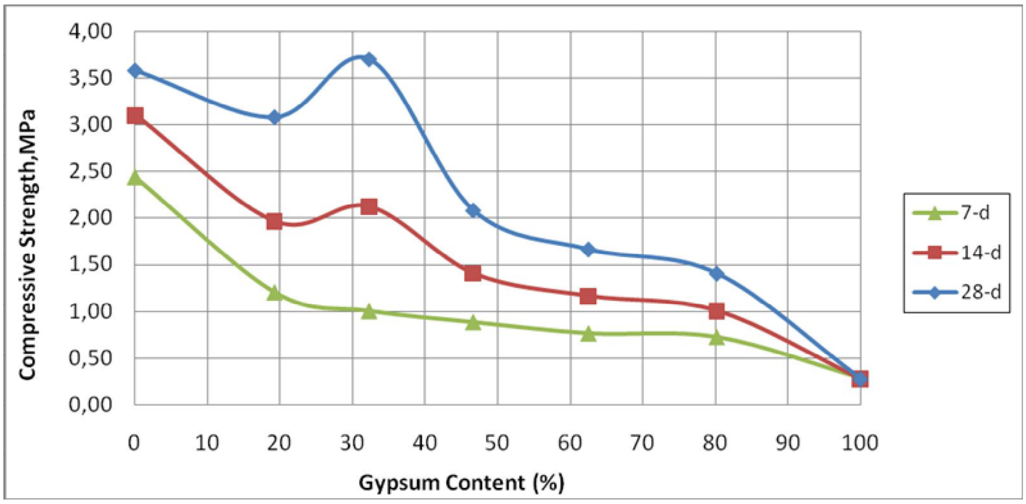

Figure A.8 "Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured for 12 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

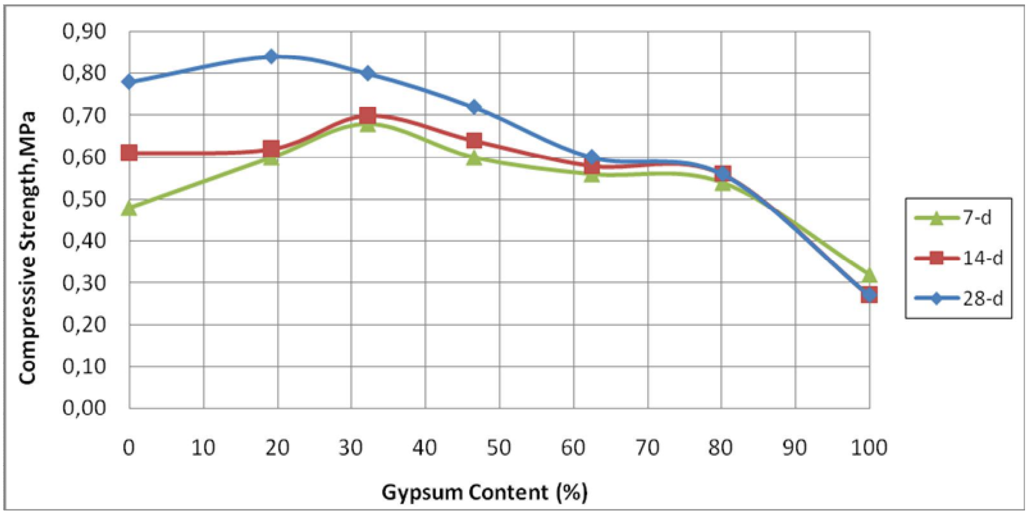

Figure A.9 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured for 12 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content” Relationships for Different Curing Times

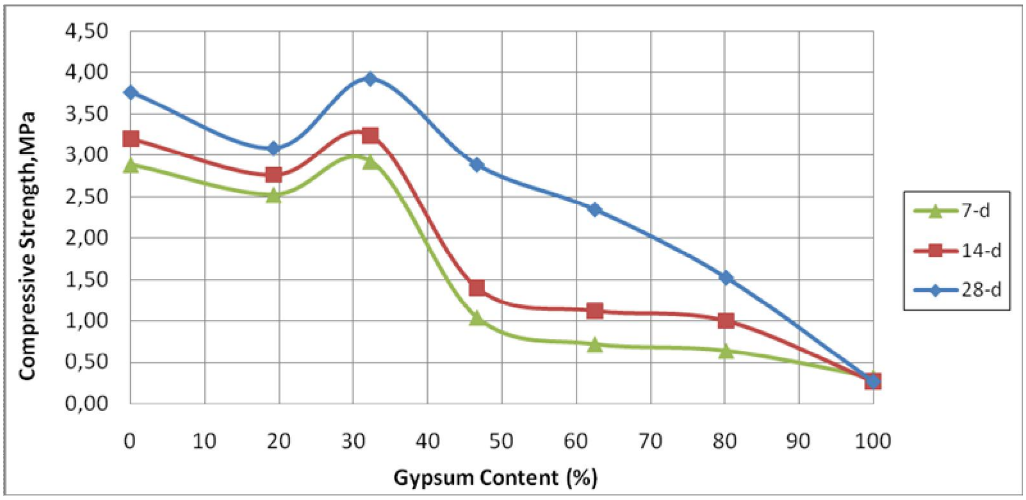

Figure A.10 “Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured for 12 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content” Relationships for Different Curing Times

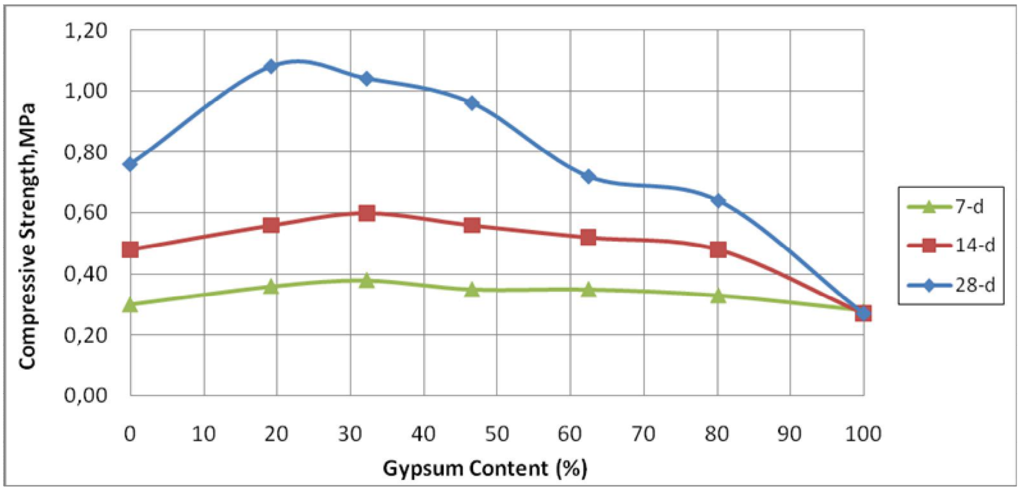

Figure A.11 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

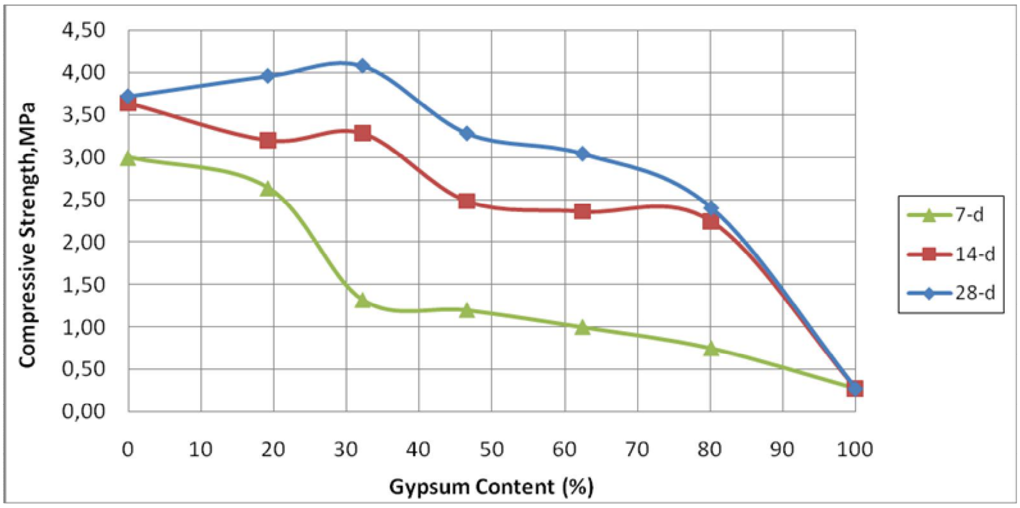

Figure A.12 "Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

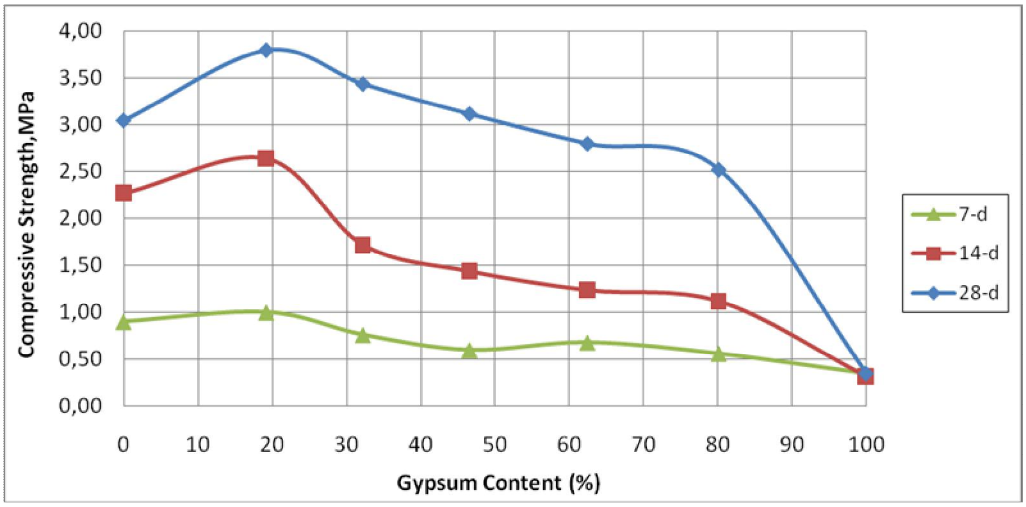

Figure A.13 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

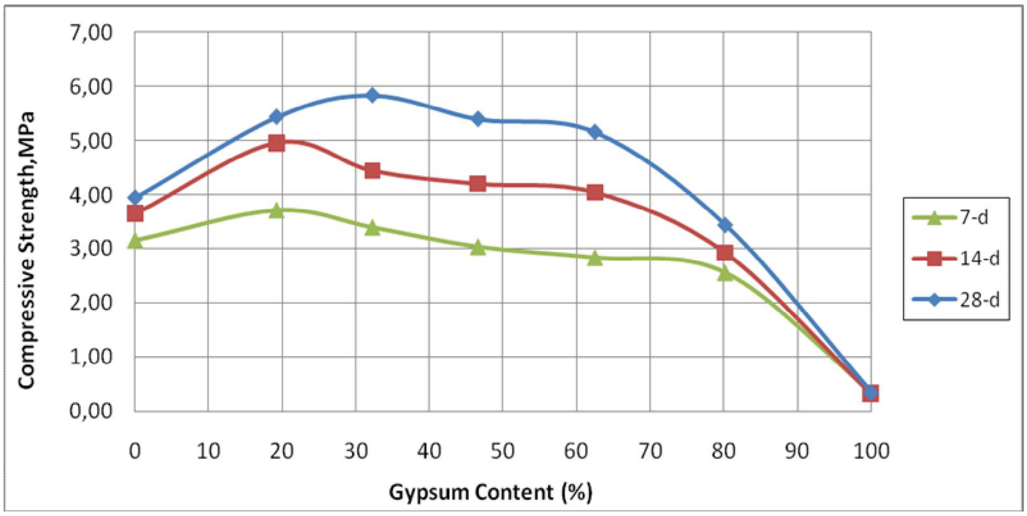

Figure A.14 "Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Days

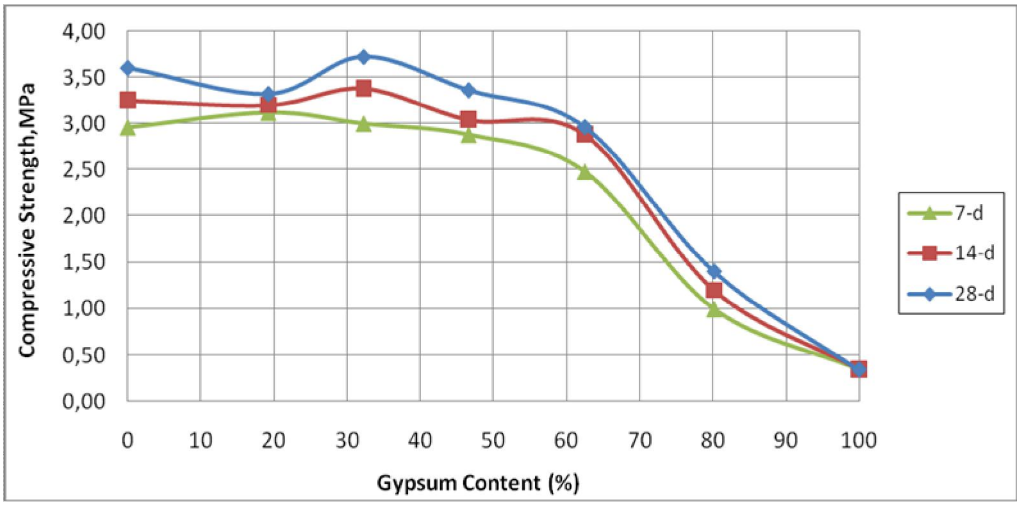

Figure A.15 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured for 72 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

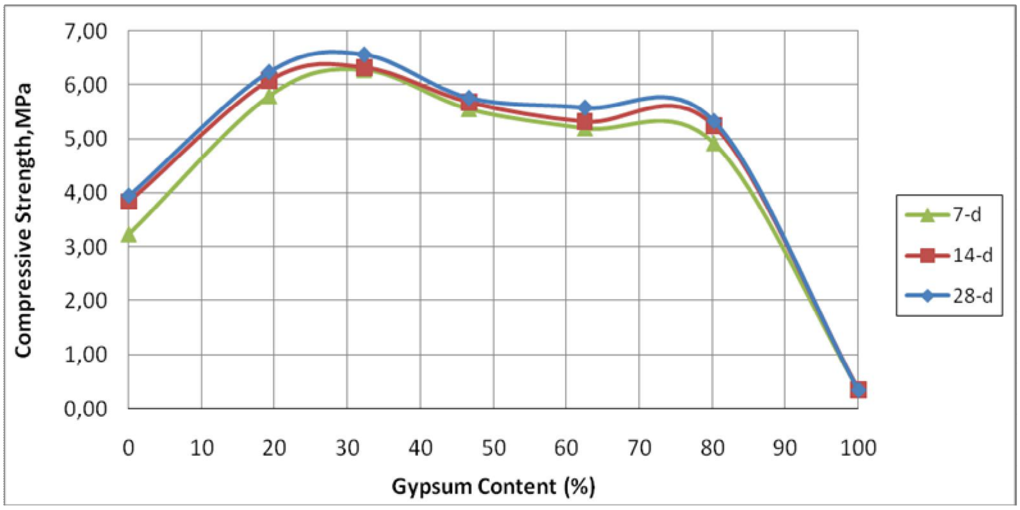

Figure A.16 "Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured for 72 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

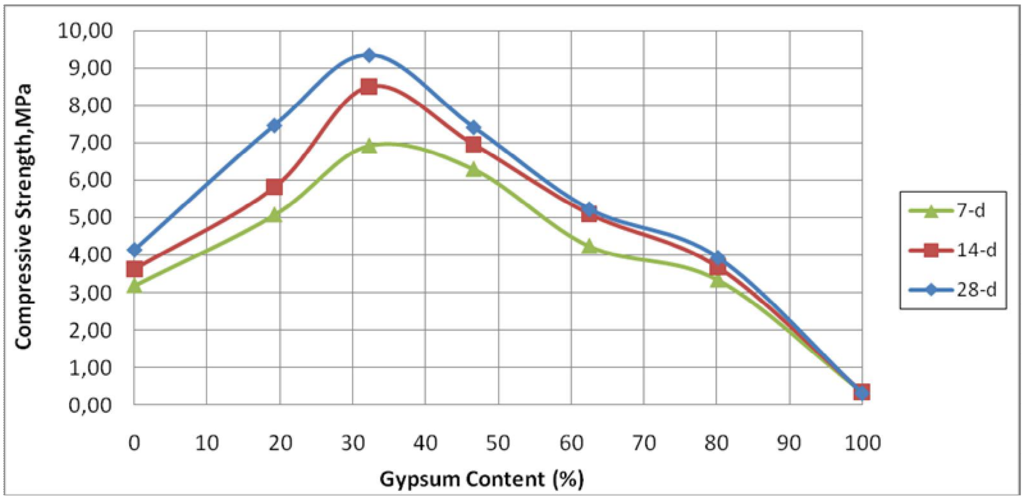

Figure A.17 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash and Hydrated Lime Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

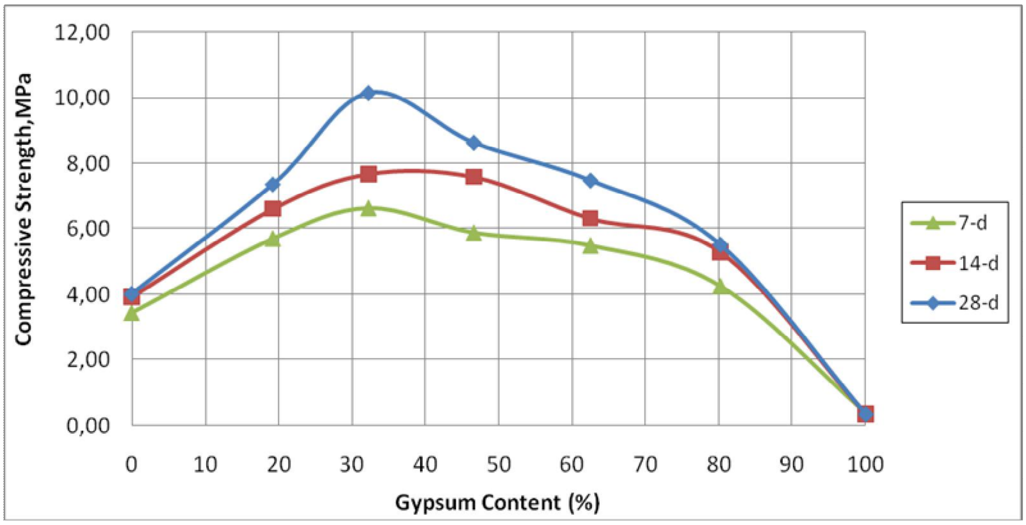

Figure A.18 "Compressive Strengths of the Mixes Including Gypsum, Slag and Hydrated Lime Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Gypsum Content" Relationships for Different Curing Times

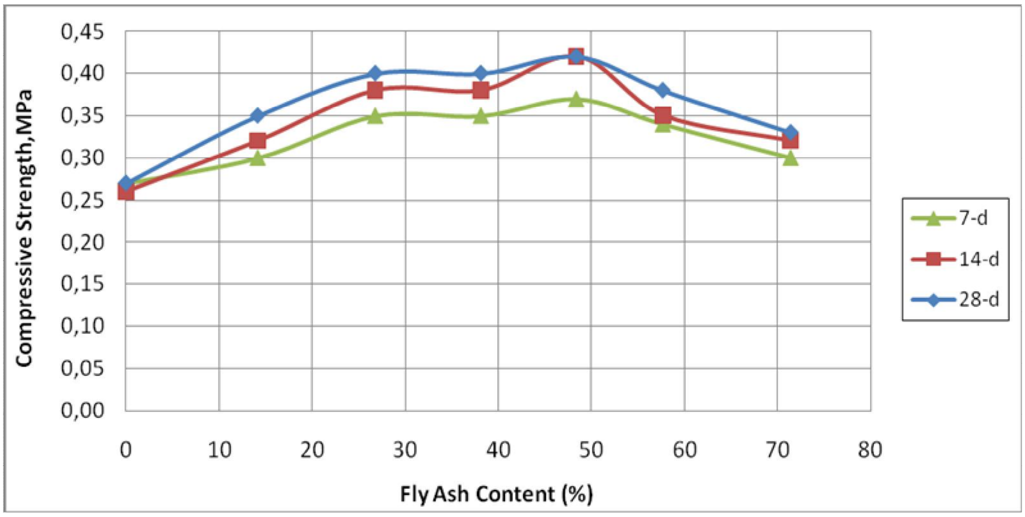

Figure A.19 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured at 20 ^{0}C vs. Fly Ash Content" Relationships for Different Curing Times

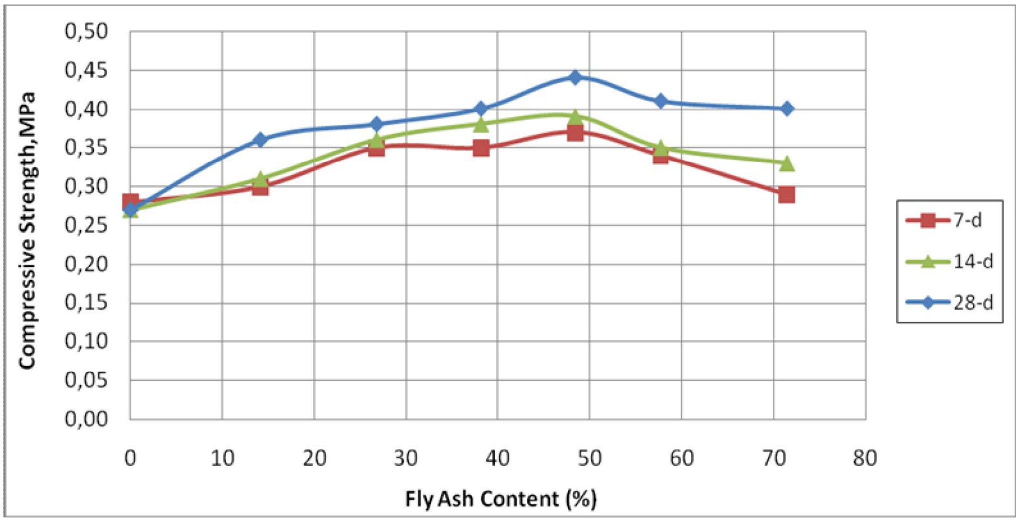

Figure A.20 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Fly Ash Content" Relationships for Different Curing Times

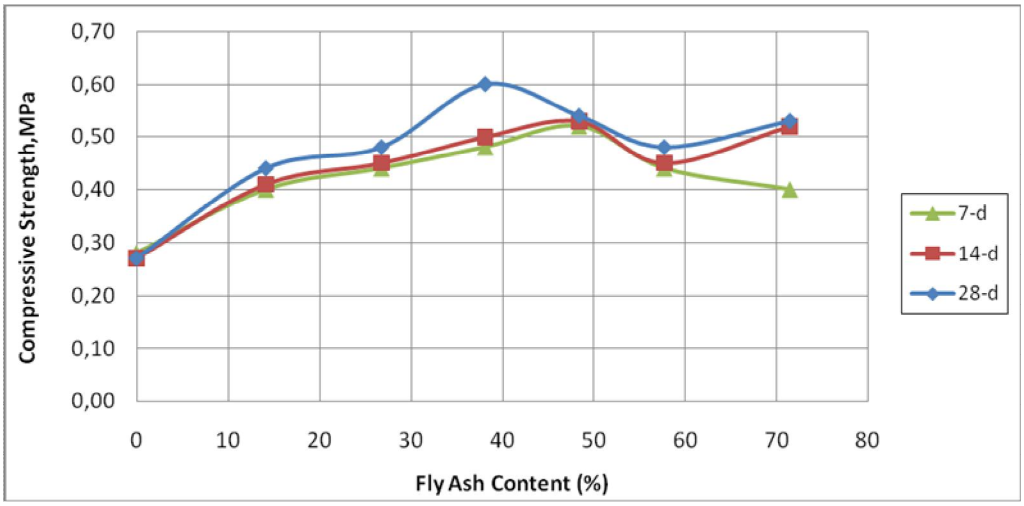

Figure A.21 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Fly Ash Content” Relationships for Different Curing Times

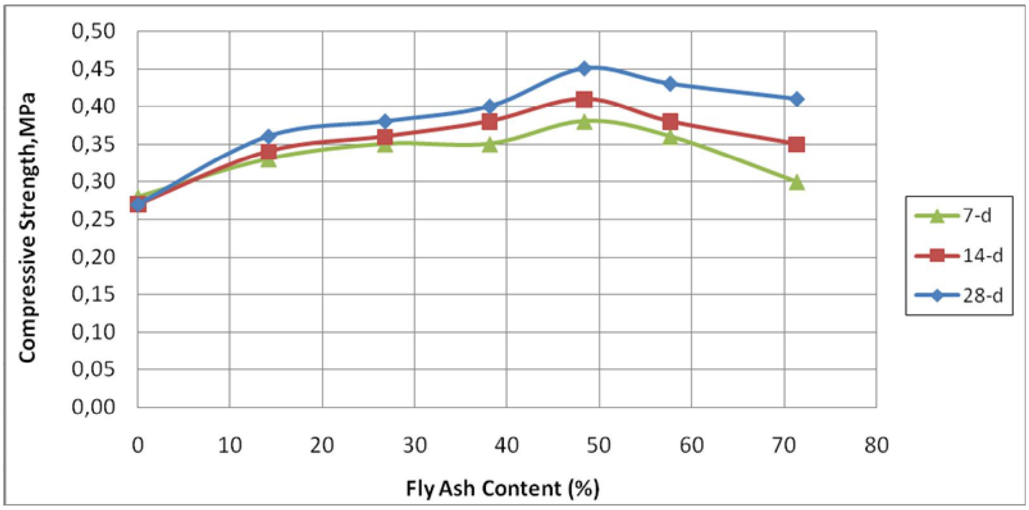

Figure A.22 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 12 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Fly Ash Content” Relationships for Different Curing Times

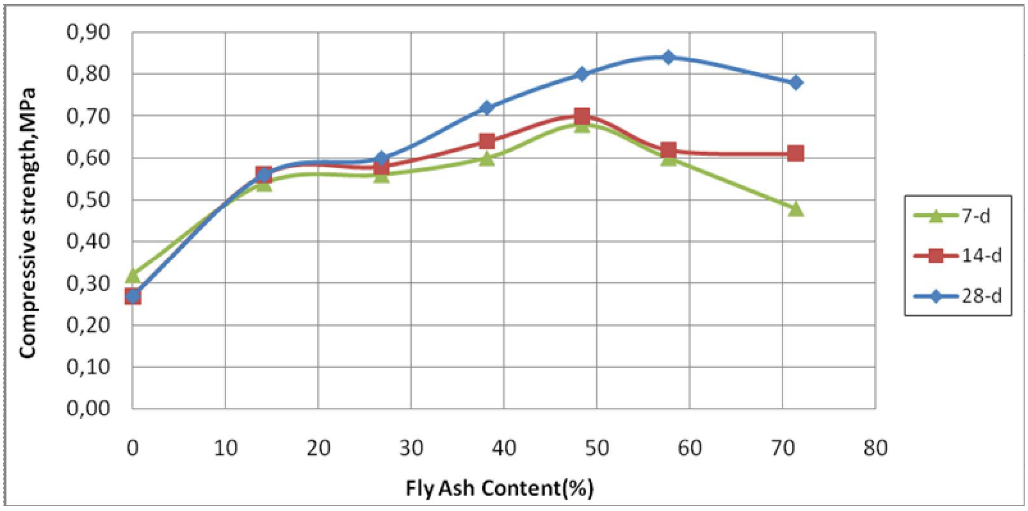

Figure A.23 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 12 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Fly Ash Content” Relationships for Different Curing Times

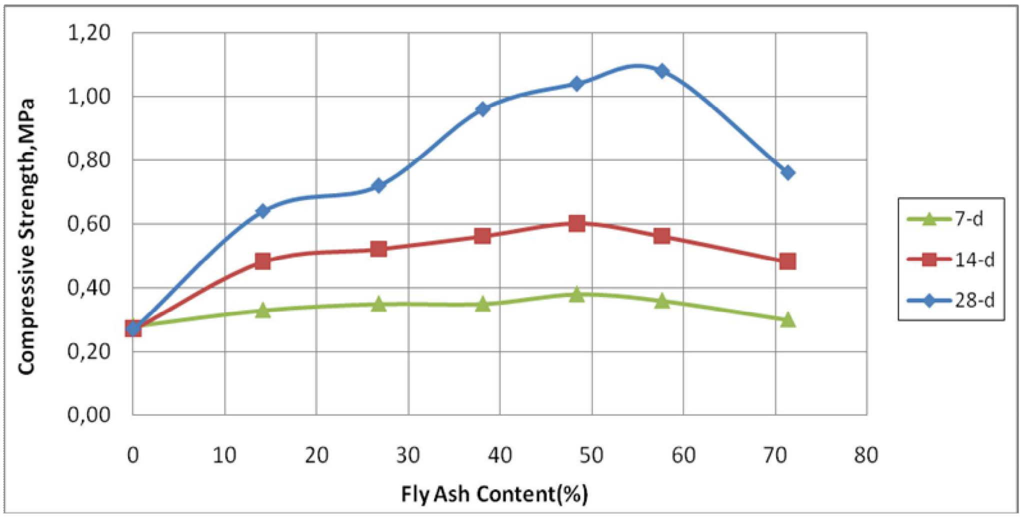

Figure A.24 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Fly Ash Content” Relationships for Different Curing Times

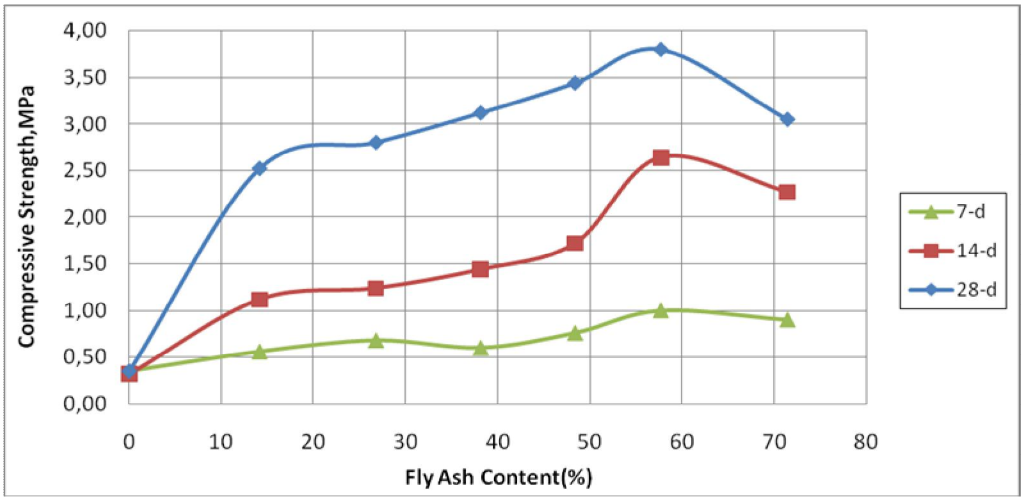

Figure A.25 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Fly Ash Content” Relationships for Different Curing Times

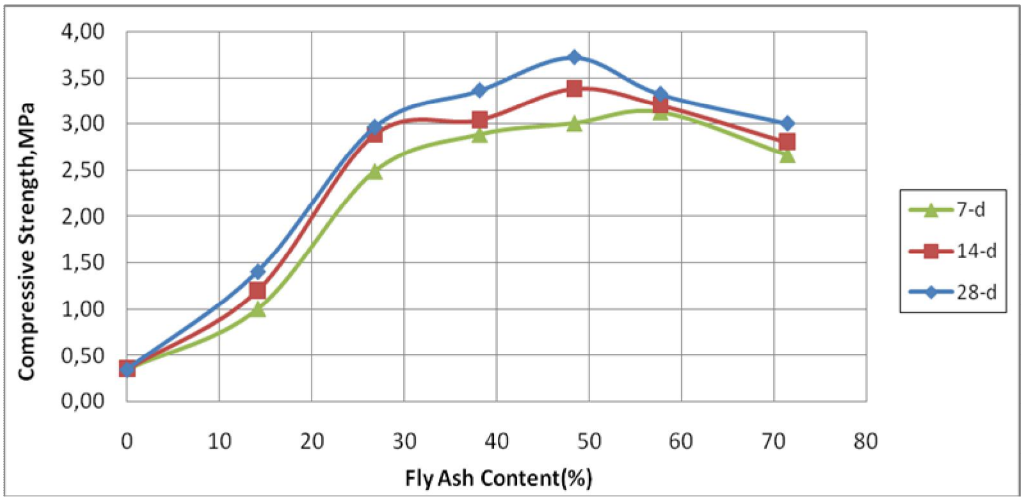

Figure A.26 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 72 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Fly Ash Content” Relationships for Different Curing Times

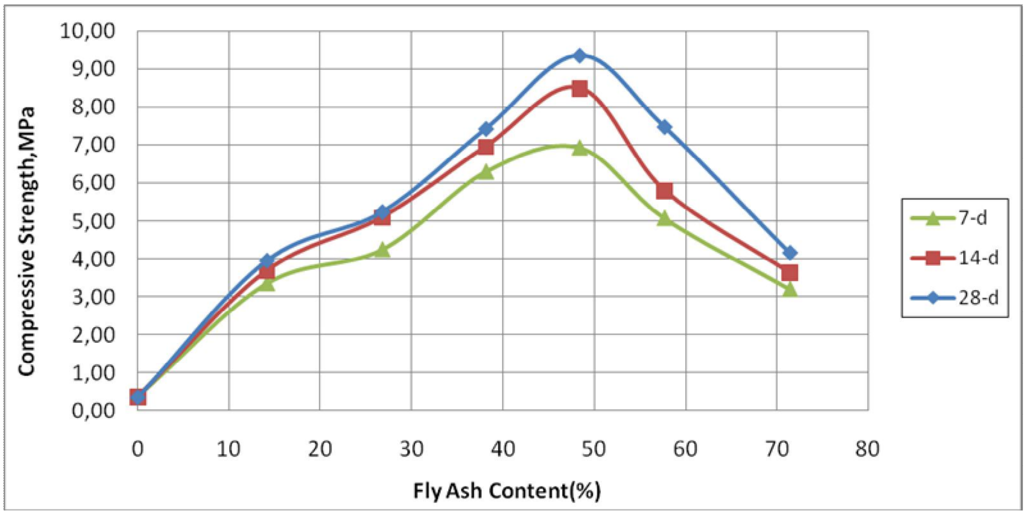

Figure A.27 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Fly Ash Content" Relationships for Different Curing Times

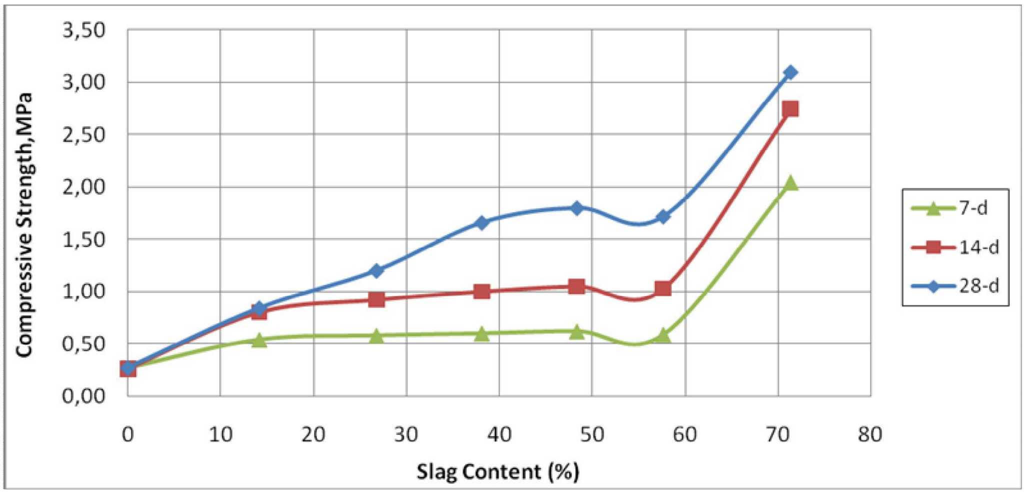

Figure A.28 "Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured at 20 ^{0}C vs. Slag Content" Relationships for Different Curing Times

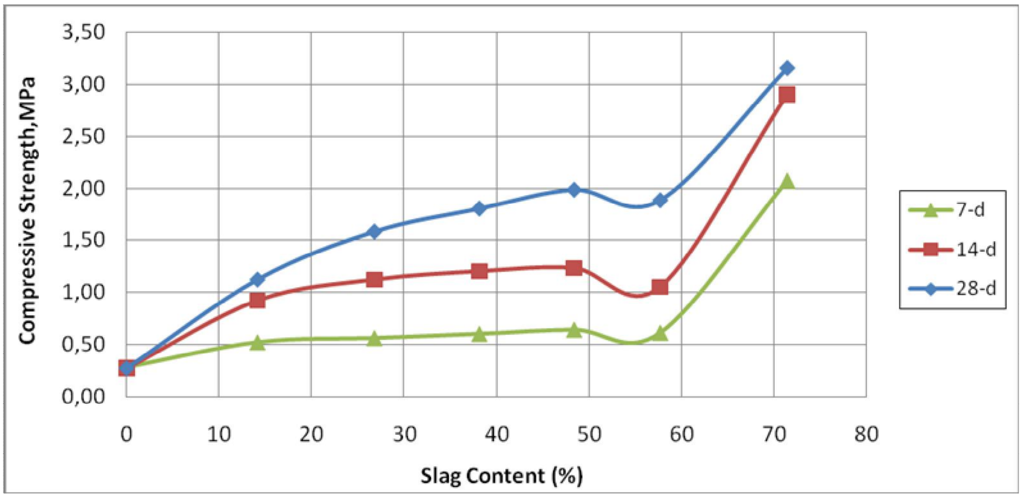

Figure A.29 "Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Slag Content" Relationships for Different Curing Times

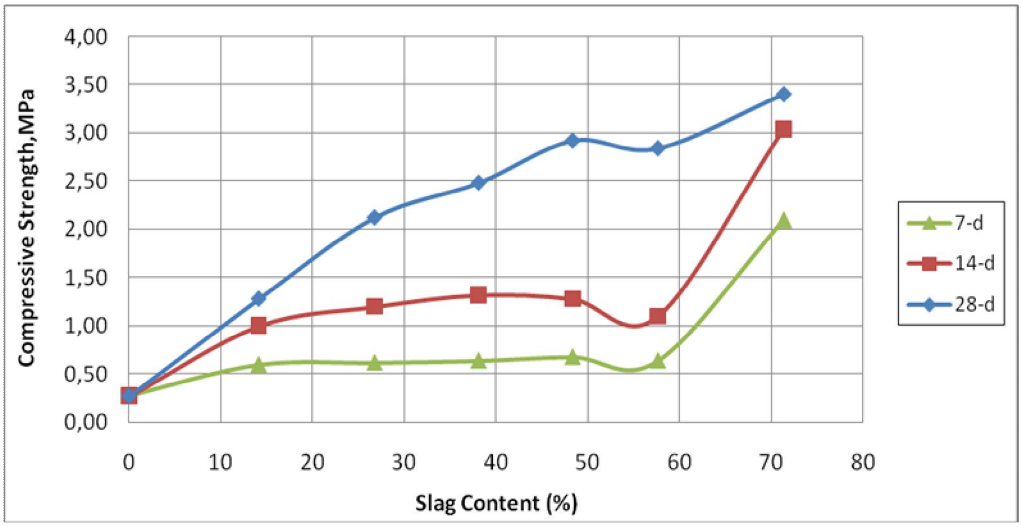

Figure A.30 "Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Slag Content" Relationships for Different Curing Times

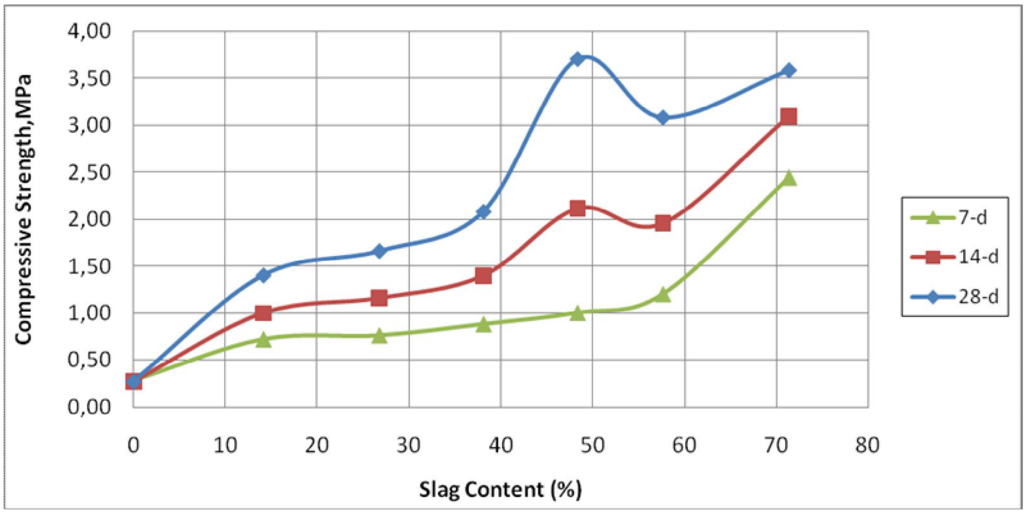

Figure A.31 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 12 Hours in a 50 ^{0}C Oven Then, Cured in Water at 20 ^{0}C vs. Slag Content” Relationships for Different Curing Times

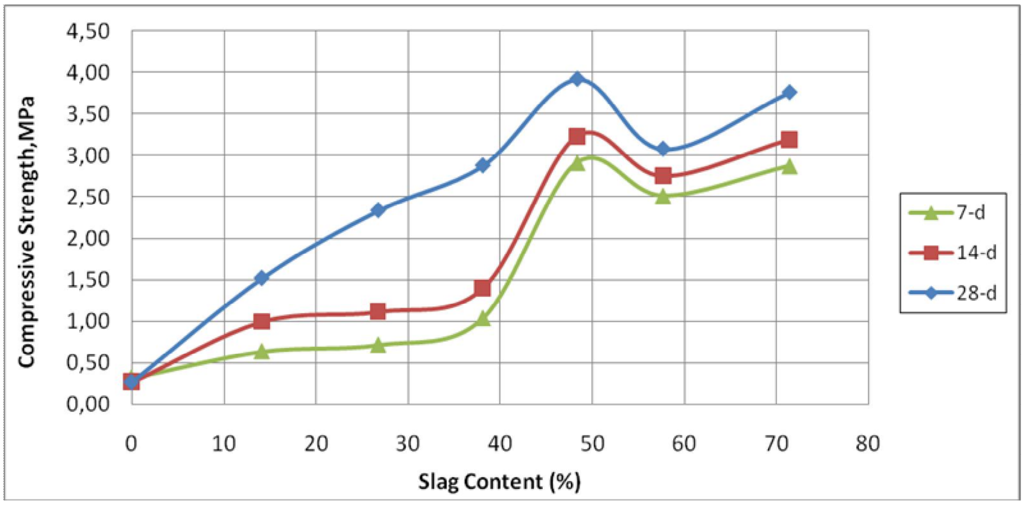

Figure A.32 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 12 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Slag Content” Relationships for Different Curing Times

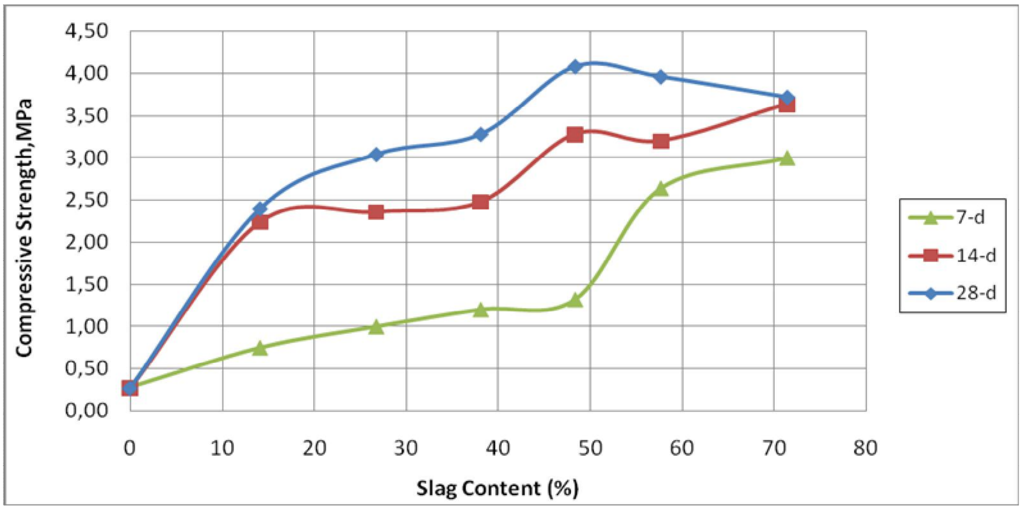

Figure A.33 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Slag Content” Relationships for Different Curing Times

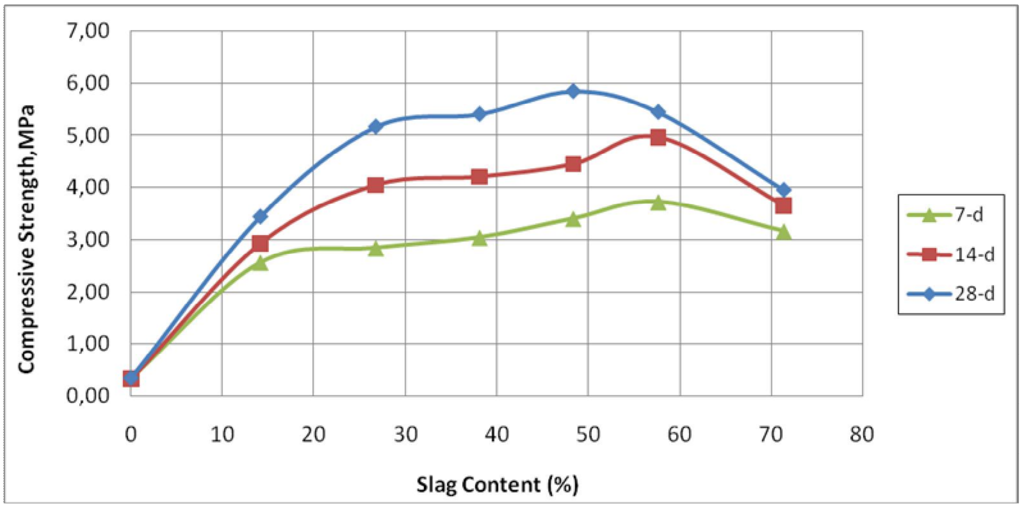

Figure A.34 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Slag Content” Relationships for Different Curing Times

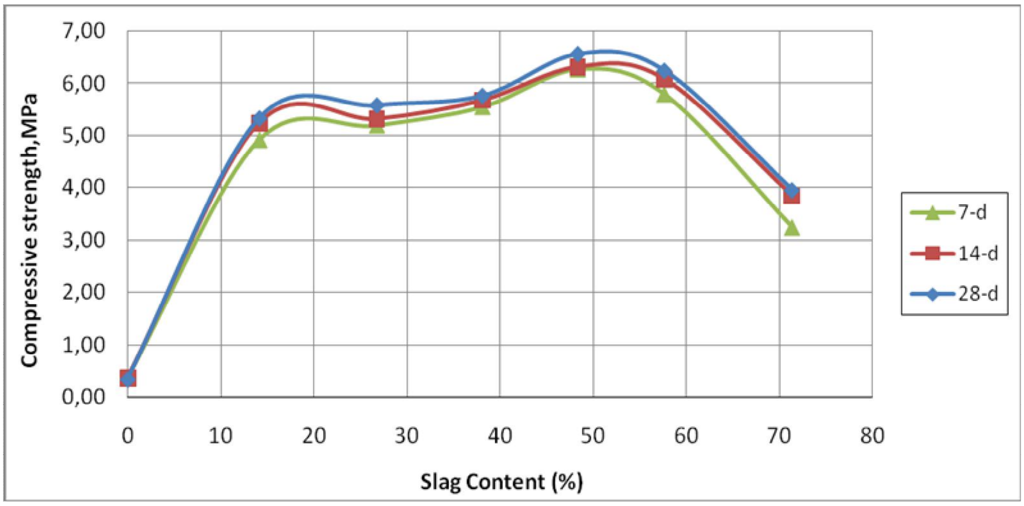

Figure A.35 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 72 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Slag Content” Relationships for Different Curing Times

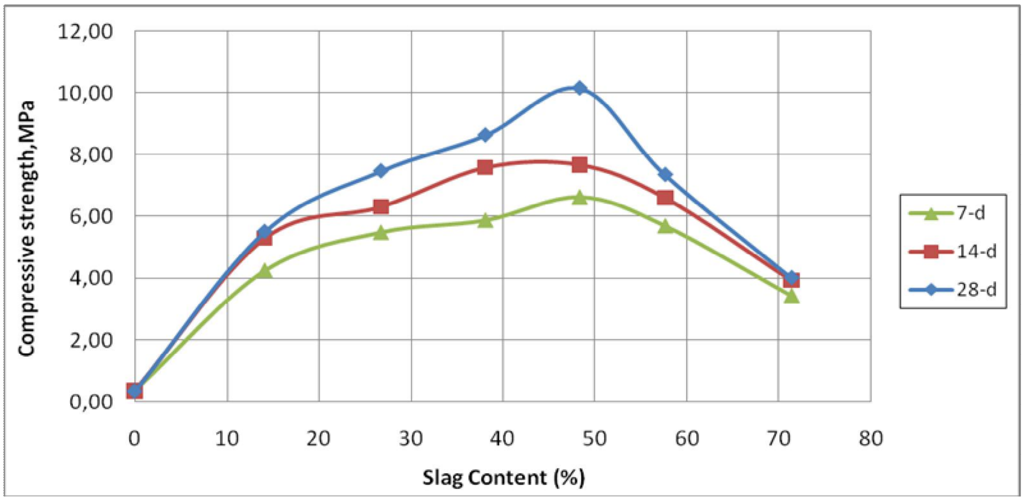

Figure A.36 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Slag Content” Relationships for Different Curing Times

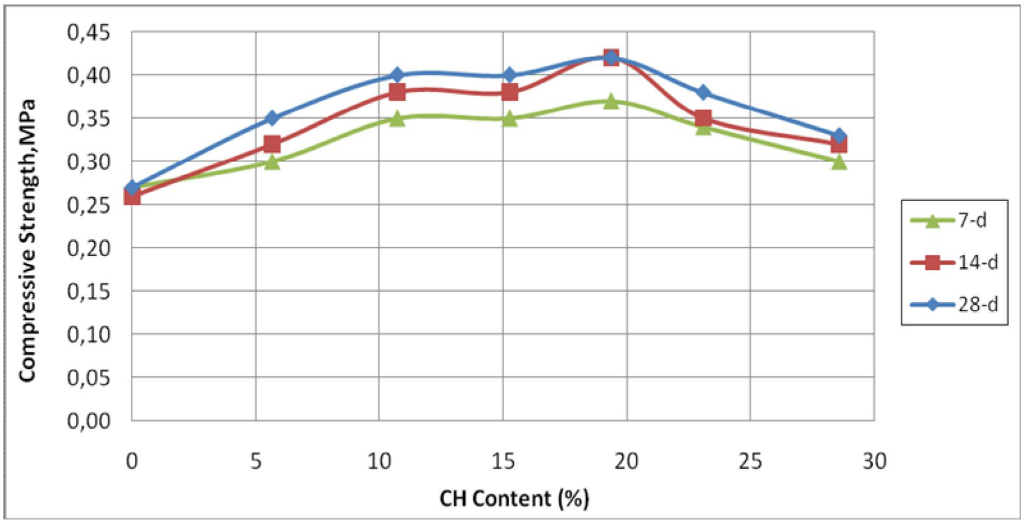

Figure A.37 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured at 20 ^{0}C vs. Hydrated Lime (CH) Content” Relationships for Different Curing Times

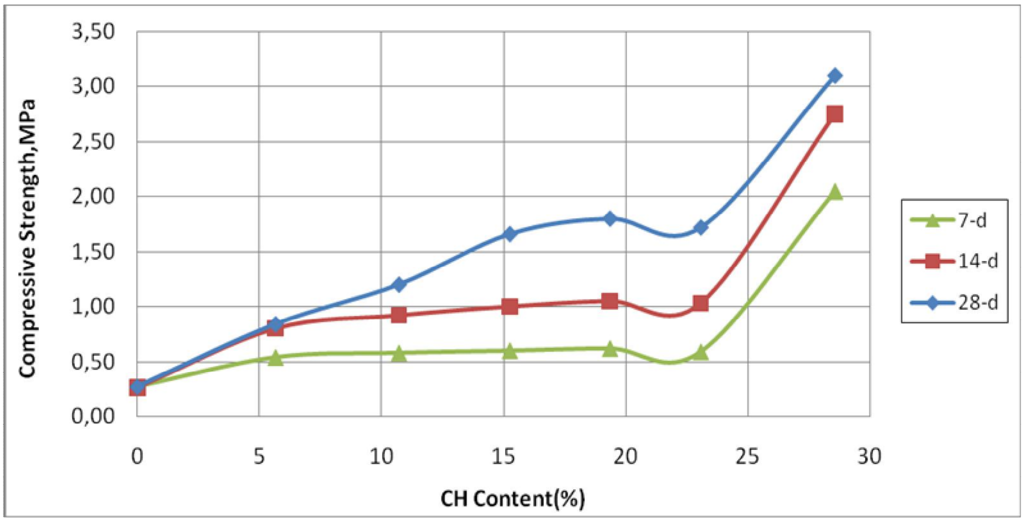

Figure A.38 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured at 20 ^{0}C vs. Hydrated Lime (CH) Content” Relationships for Different Curing Times

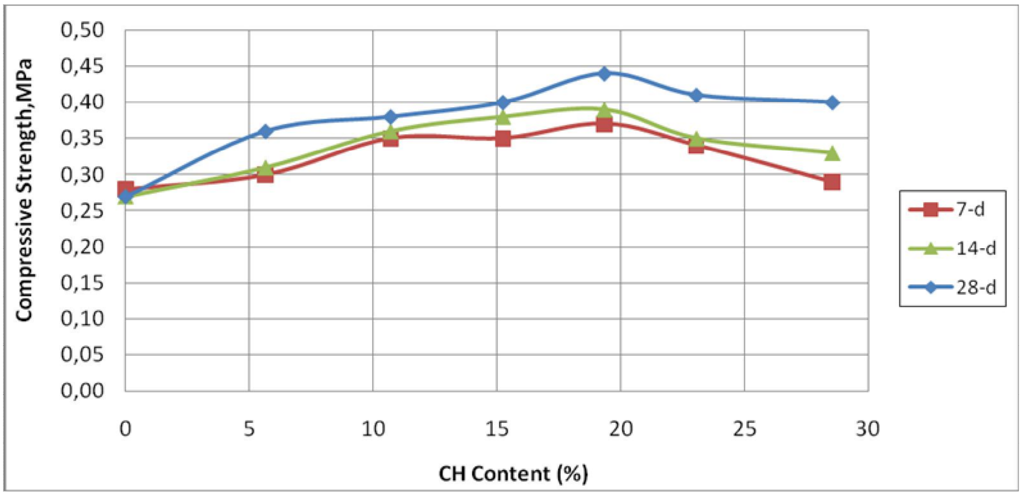

Figure A.39 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

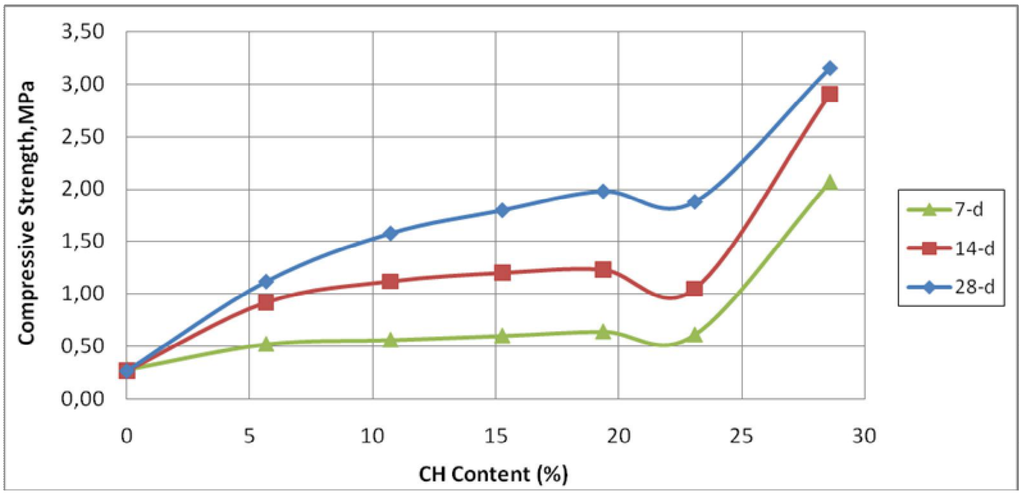

Figure A.40 "Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 4 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

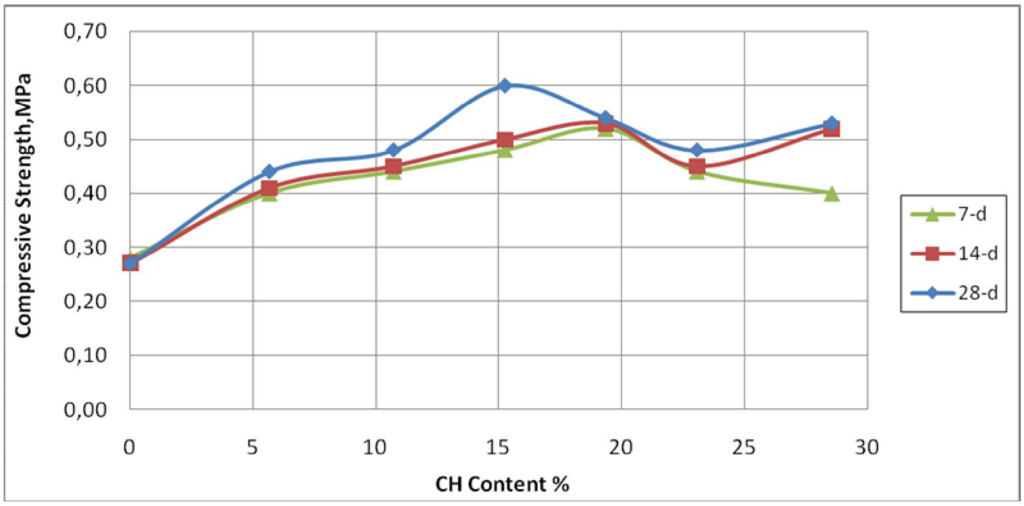

Figure A.41 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

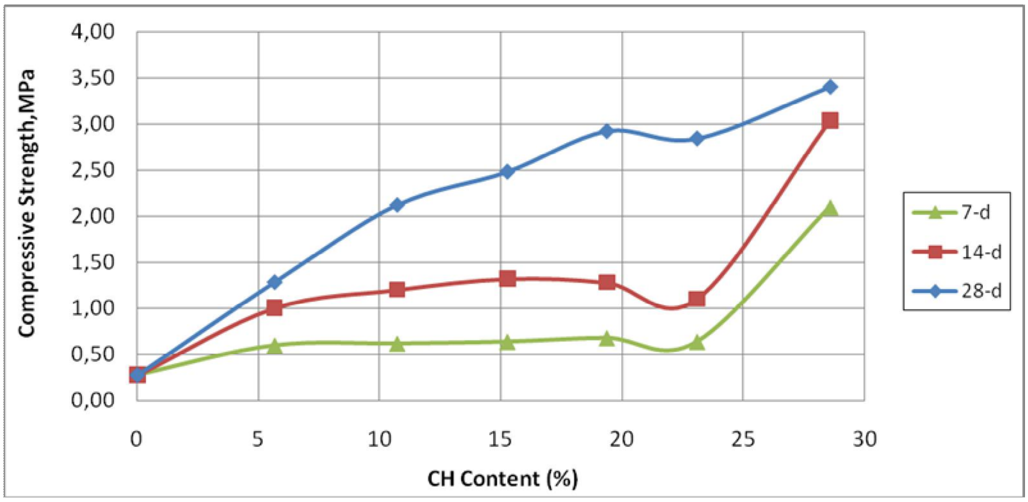

Figure A.42 "Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 4 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

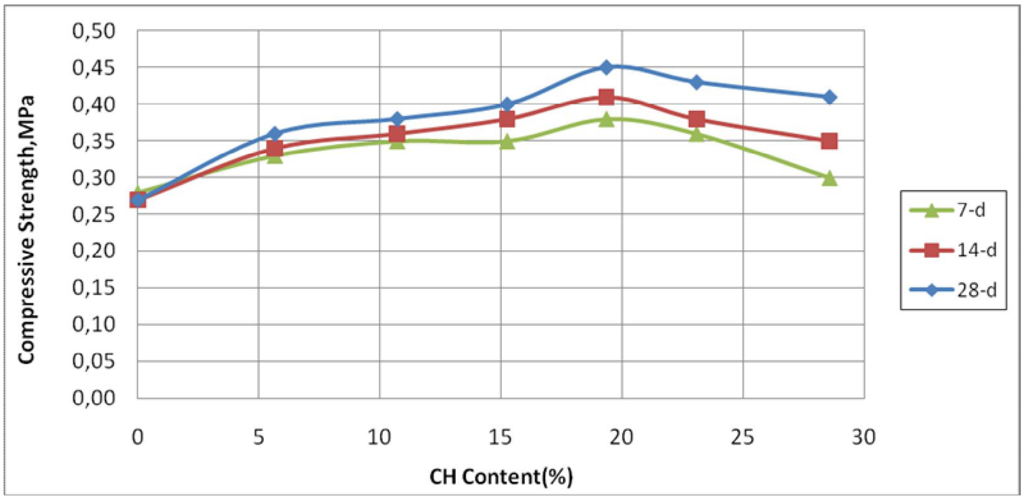

Figure A.43 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 12 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

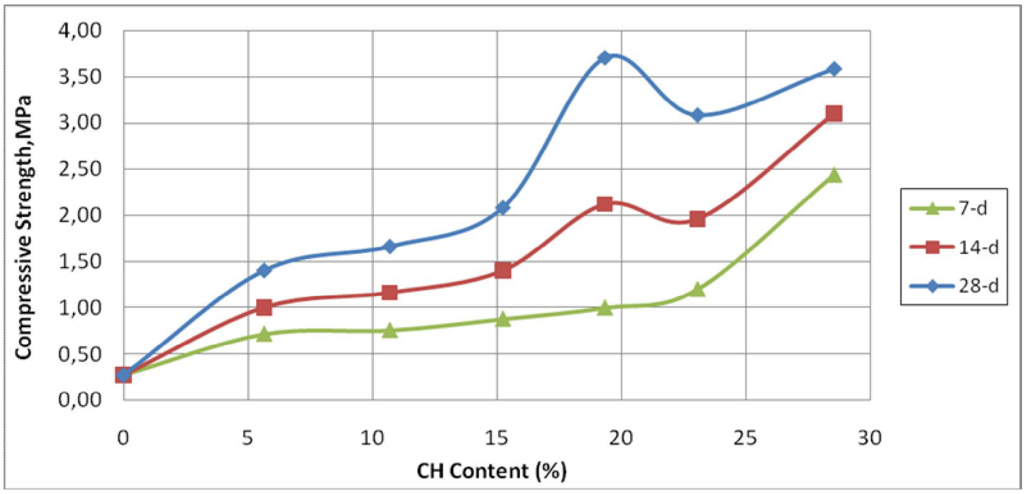

Figure A.44 "Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 12 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

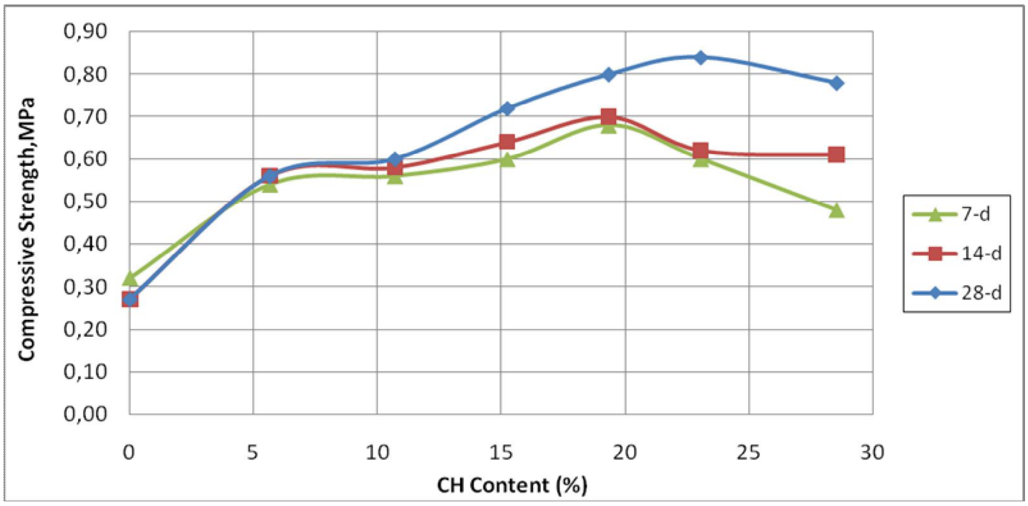

Figure A.45 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 12 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content” Relationships for Different Curing Times

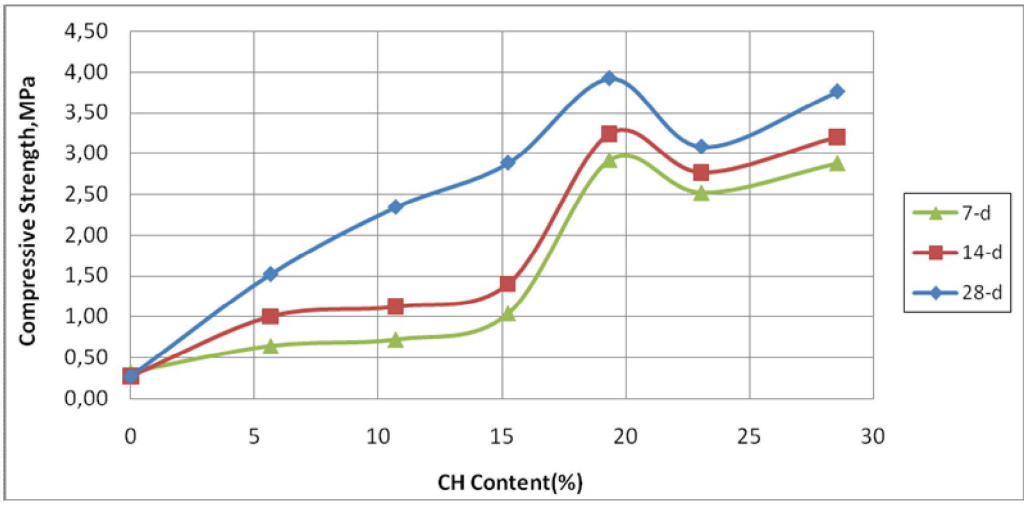

Figure A.46 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 12 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content” Relationships for Different Curing Times

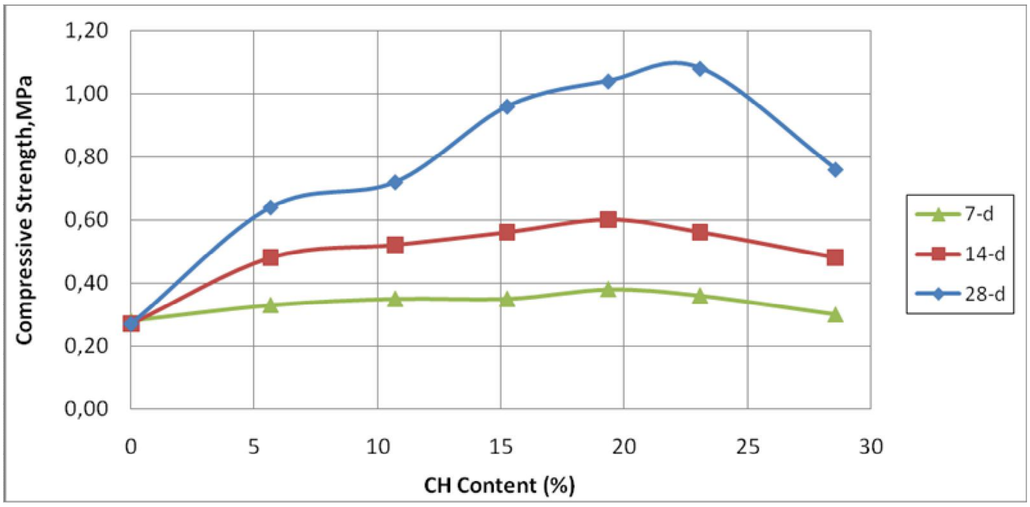

Figure A.47 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

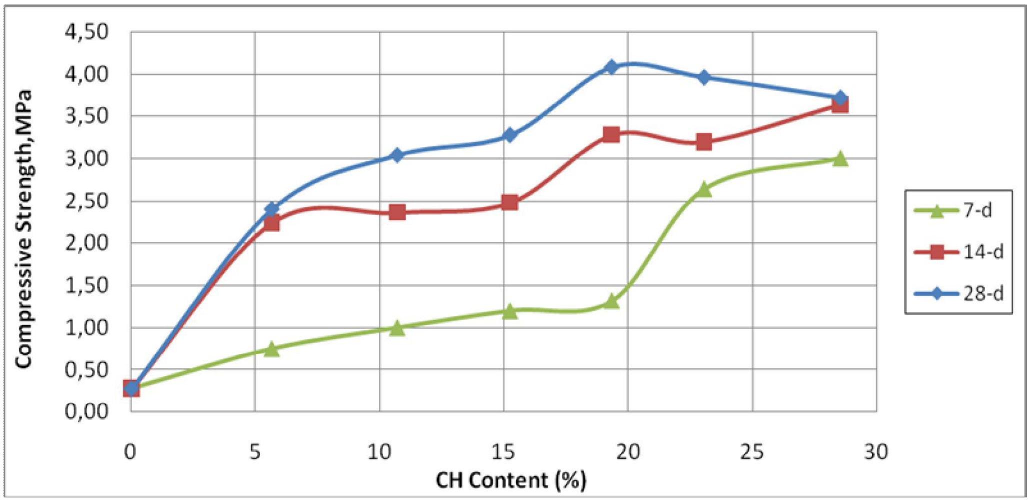

Figure A.48 "Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 24 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

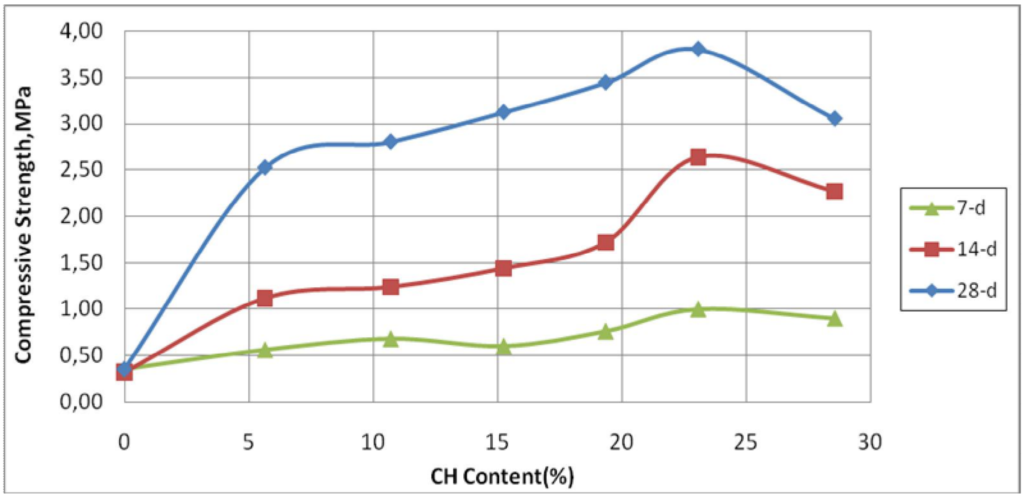

Figure A.49 "Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

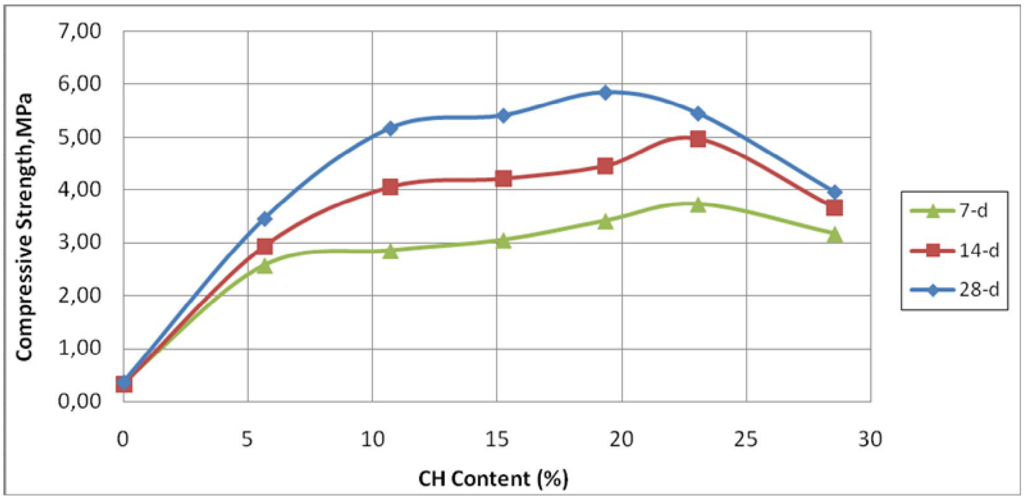

Figure A.50 "Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 24 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content" Relationships for Different Curing Times

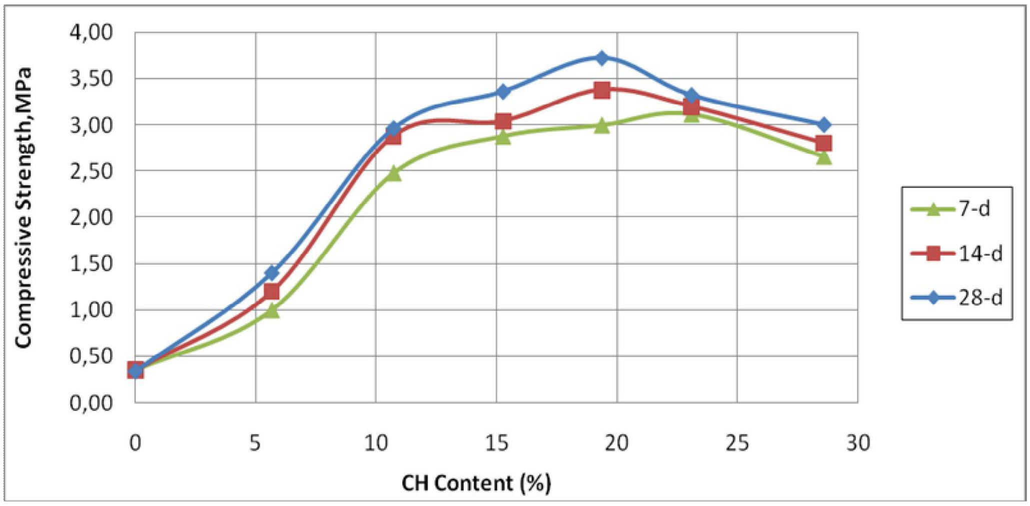

Figure A.51 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 72 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content” Relationships for Different Curing Times

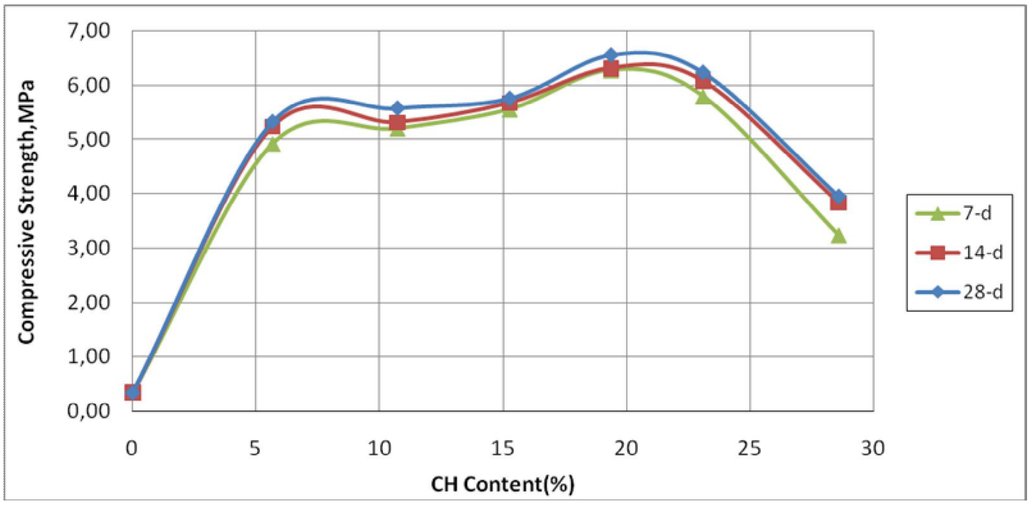

Figure A.52 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 72 Hours in a 50 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content” Relationships for Different Curing Times

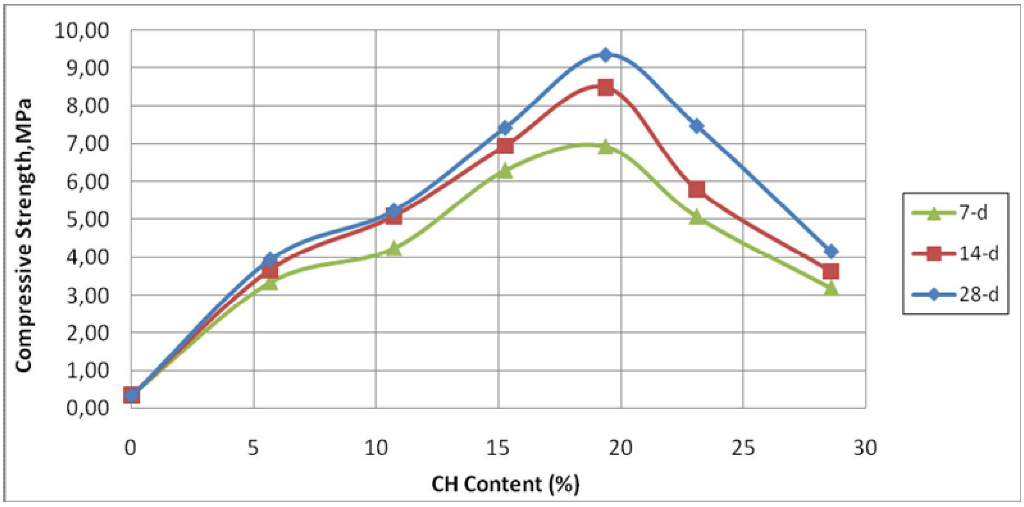

Figure A.53 “Compressive Strengths of the Mixes Including Gypsum, Fly Ash, Hydrated Lime Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content” Relationships for Different Curing Times

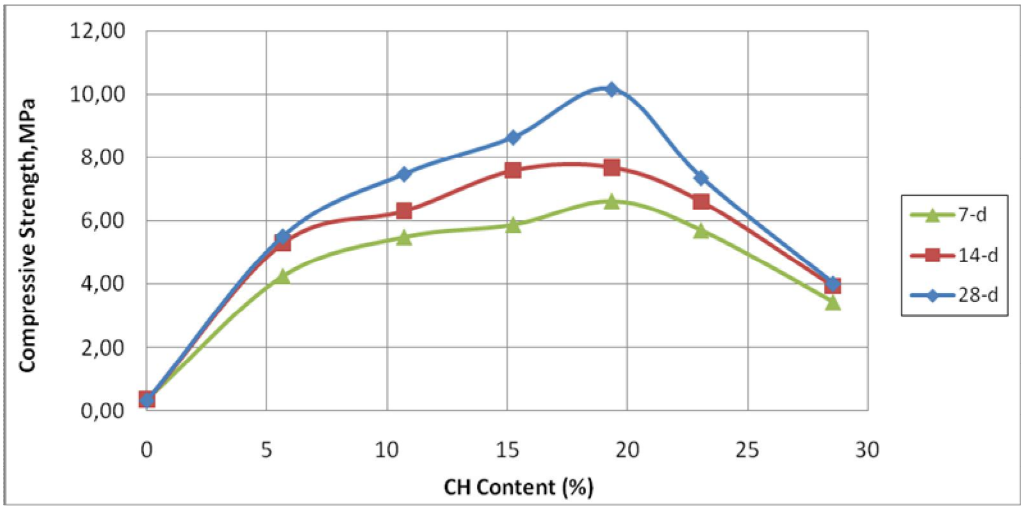

Figure A.54 “Compressive Strengths of the Mixes Including Gypsum, Slag, Hydrated Lime Cured for 72 Hours in an 80 ^{0}C Oven, Then Cured in Water at 20 ^{0}C vs. Hydrated Lime (CH) Content” Relationships for Different Curing Times

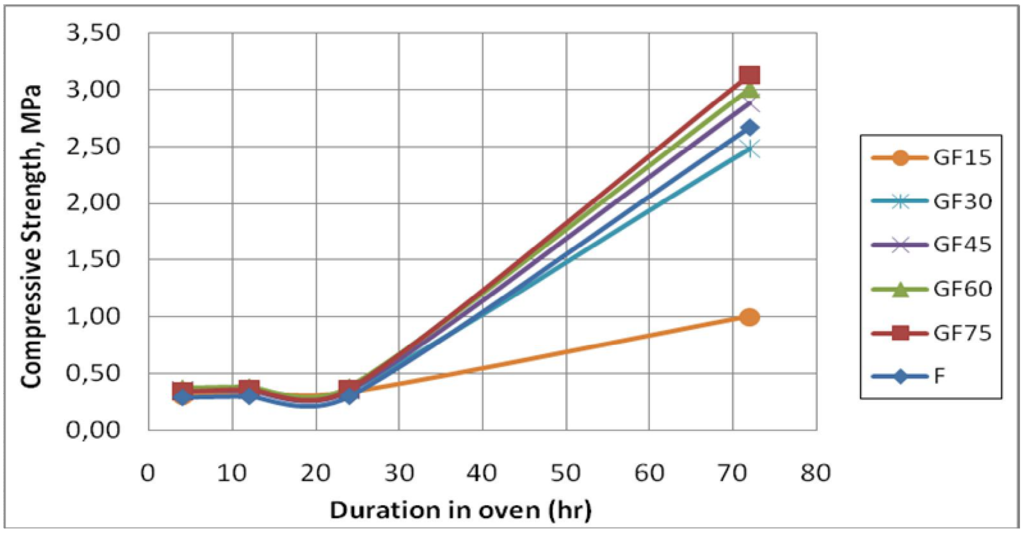

Figure A.55 “7th day Compressive Strengths of the Mixes Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Mixes Having Fly Ash as a Pozzolan

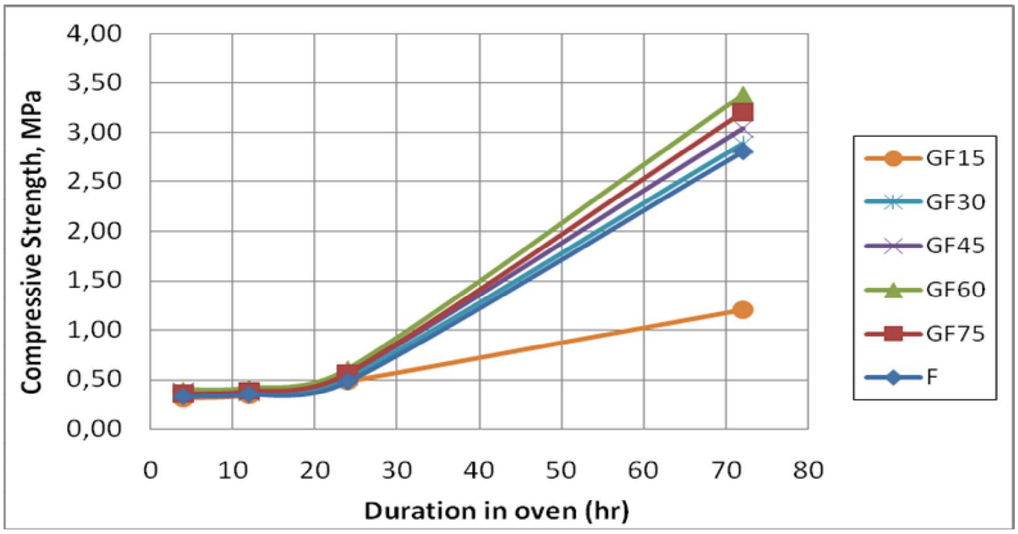

Figure A.56 “14th day Compressive Strengths of the Mixes Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Mixes Having Fly Ash as a Pozzolan

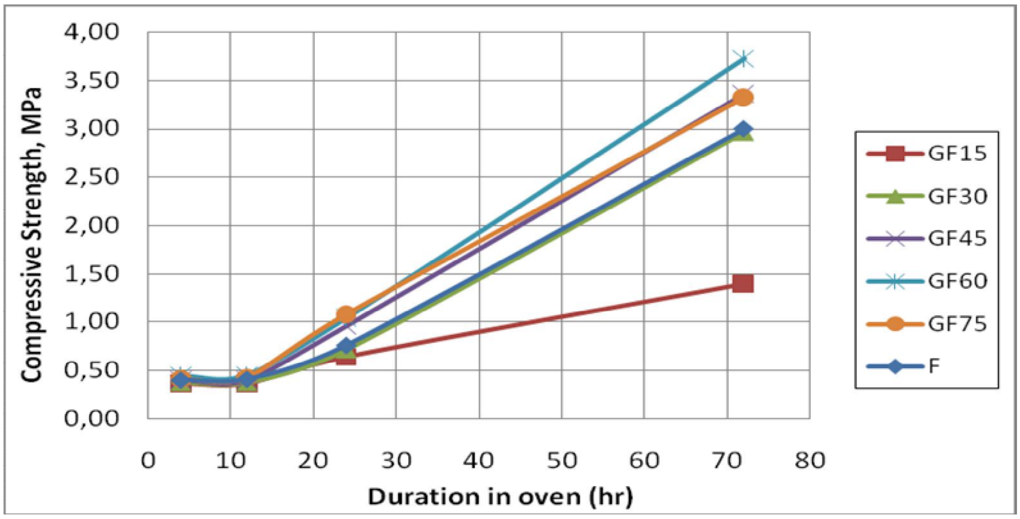

Figure A.57 “28. day Compressive Strengths of the Mixes Cured in an 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Mixes Having Fly Ash as a Pozzolan

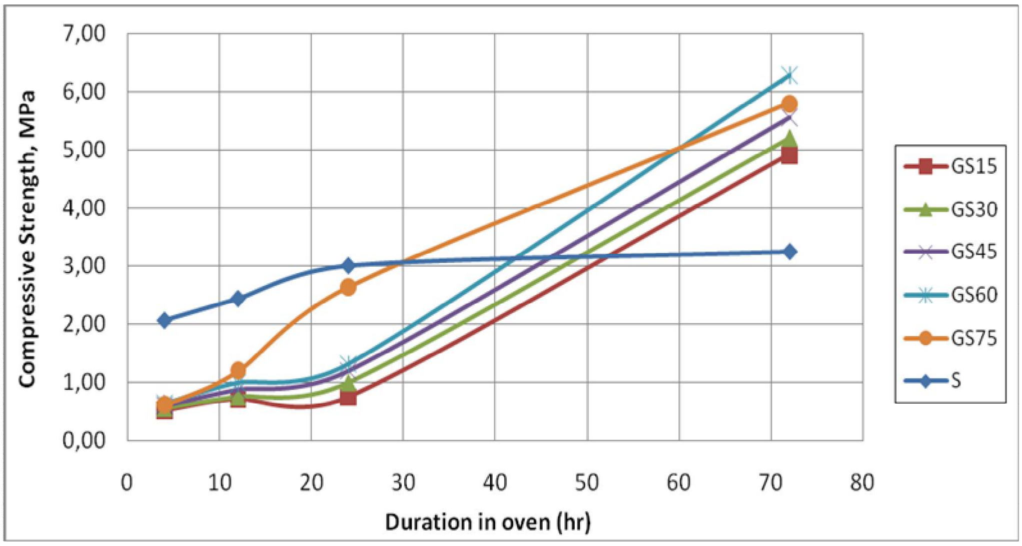

Figure A.58 “7th day Compressive Strengths of the Mixes Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Mixes Having Slag as a Pozzolan

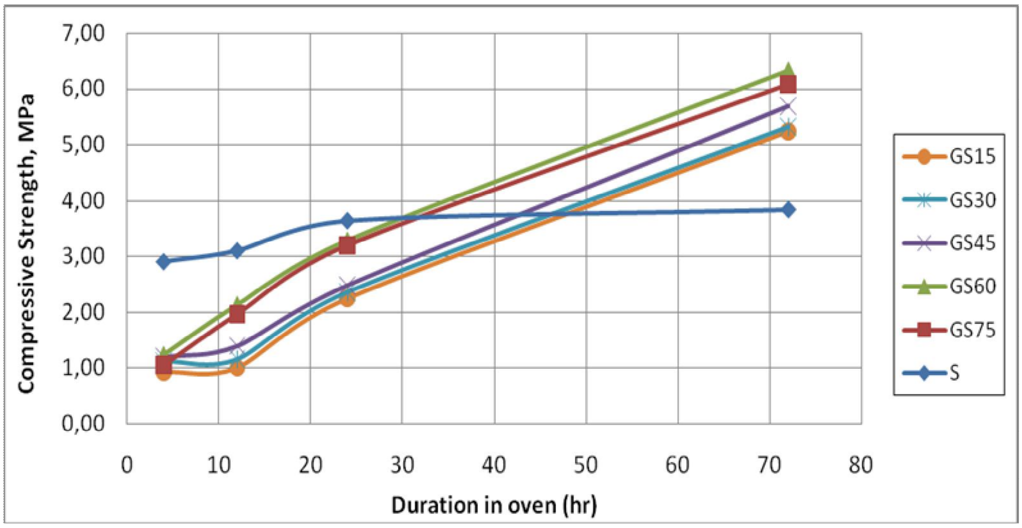

Figure A.59 "14th day Compressive Strengths of the Mixes Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Mixes Having Slag as a Pozzolan

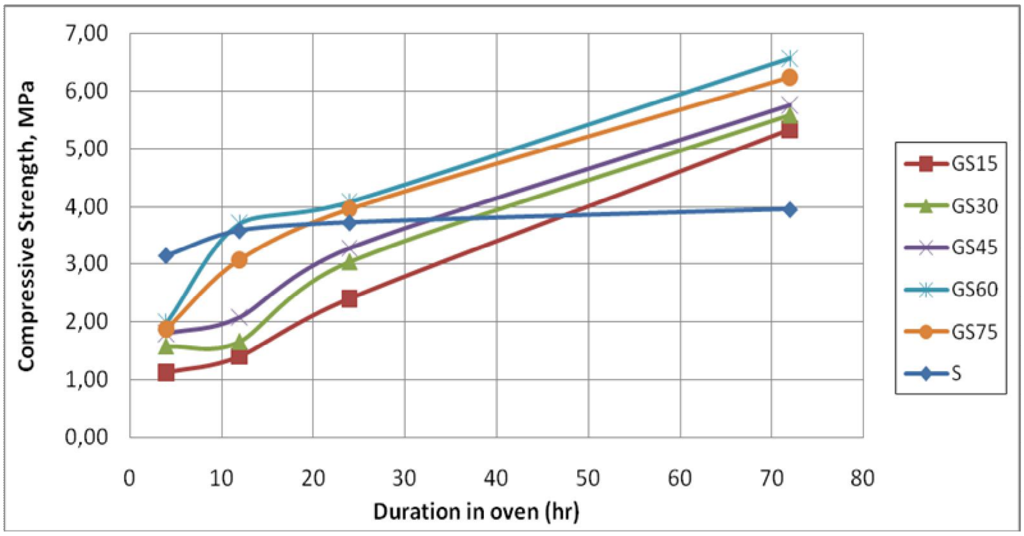

Figure A.60 "28th day Compressive Strengths of the Mixes Cured in a 50 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Mixes Having Slag as a Pozzolan

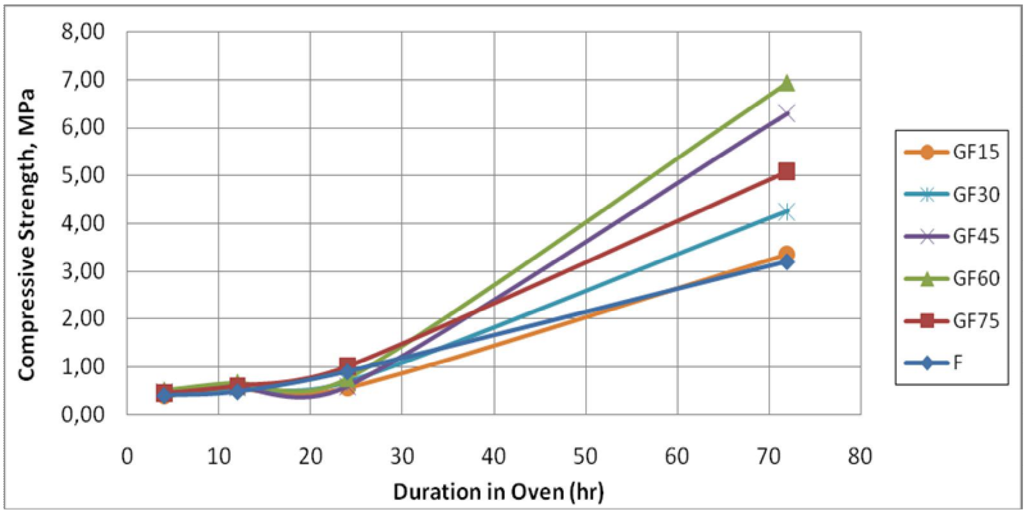

Figure A.61 “7th day Compressive Strengths of the Mixes Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Mixes Having Fly Ash as a Pozzolan

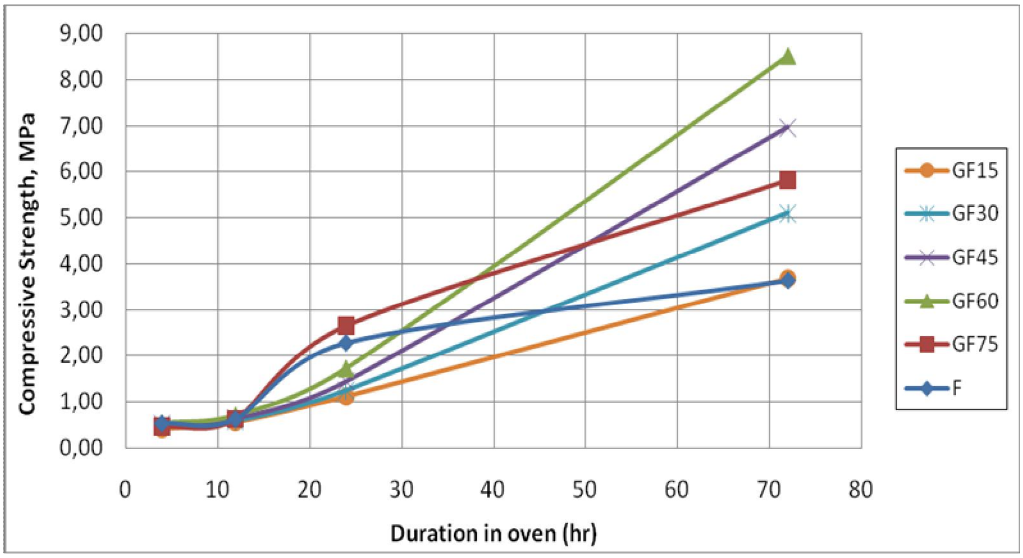

Figure A.62 “14th day Compressive Strengths of the Mixes Cured in an 80 ^{0}C Oven for a While Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Mixes Having Fly Ash as a Pozzolan

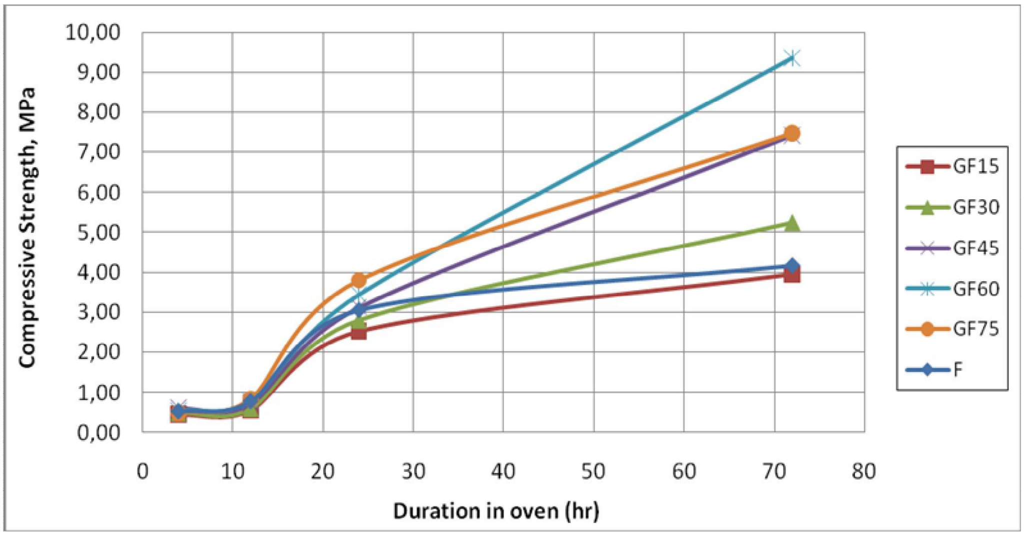

Figure A.63 "28th day Compressive Strengths of the Mixes Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Mixes Having Fly Ash as a Pozzolan

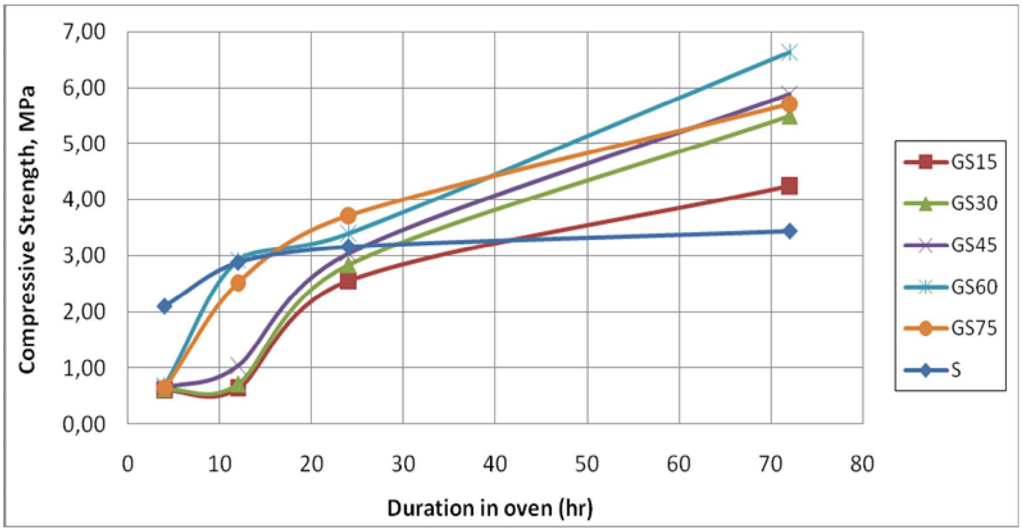

Figure A.64 "7th day Compressive Strengths of the Mixes Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Mixes Having Slag as a Pozzolan

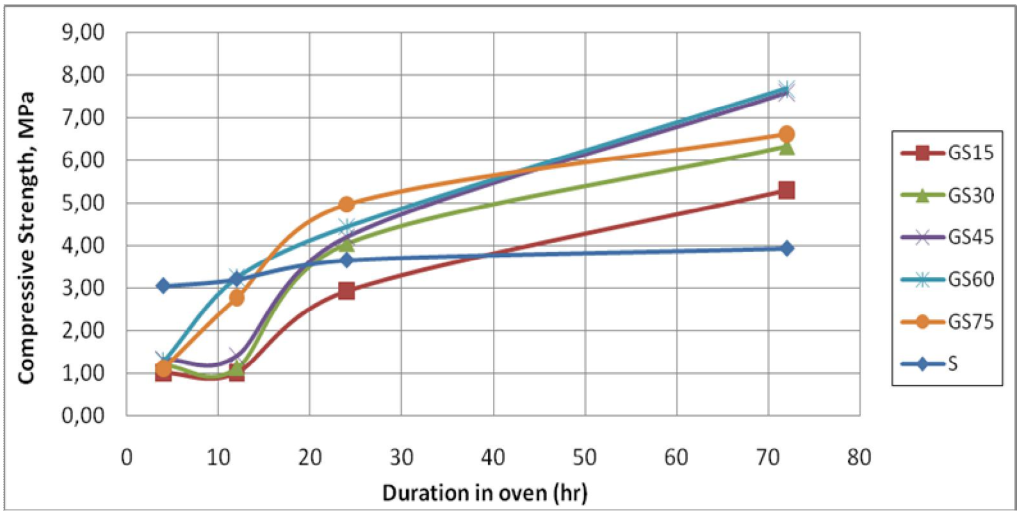

Figure A.65 “14th day Compressive Strengths of the Mixes Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Mixes Having Slag as a Pozzolan

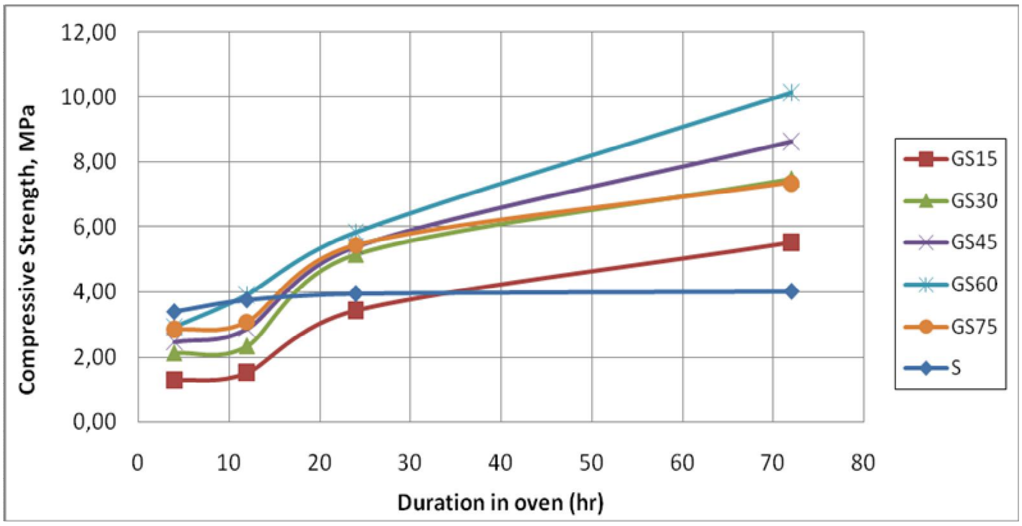

Figure A.66 “28th day Compressive Strengths of the Mixes Cured in an 80 ^{0}C Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Mixes Having Slag as a Pozzolan

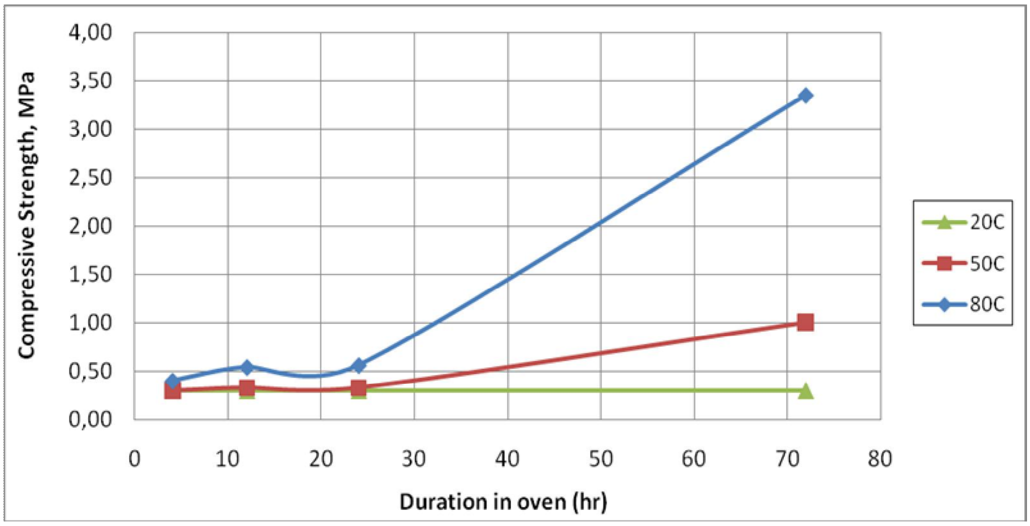

Figure A.67 “7th day Compressive Strength of GF15 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

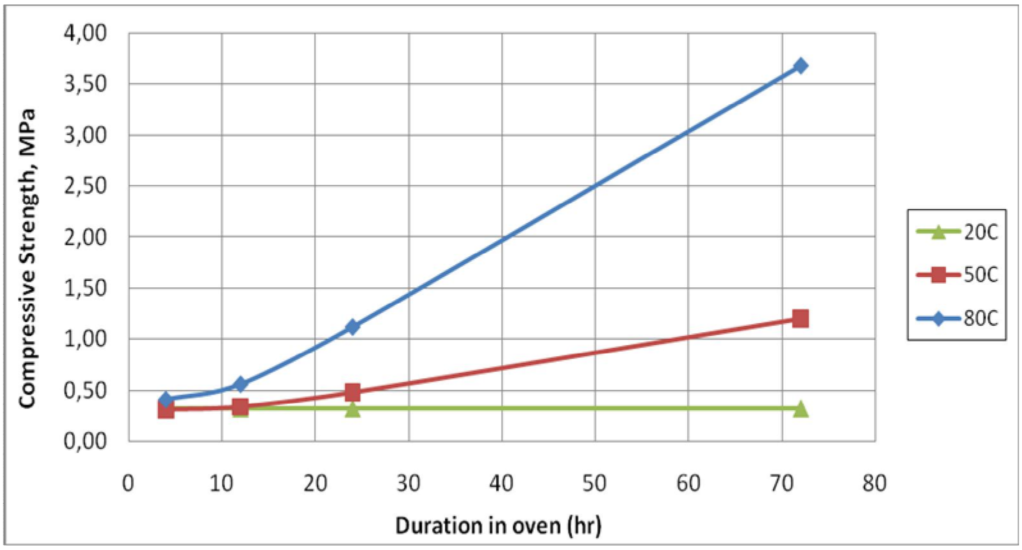

Figure A.68 “14th day Compressive Strength of GF15 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

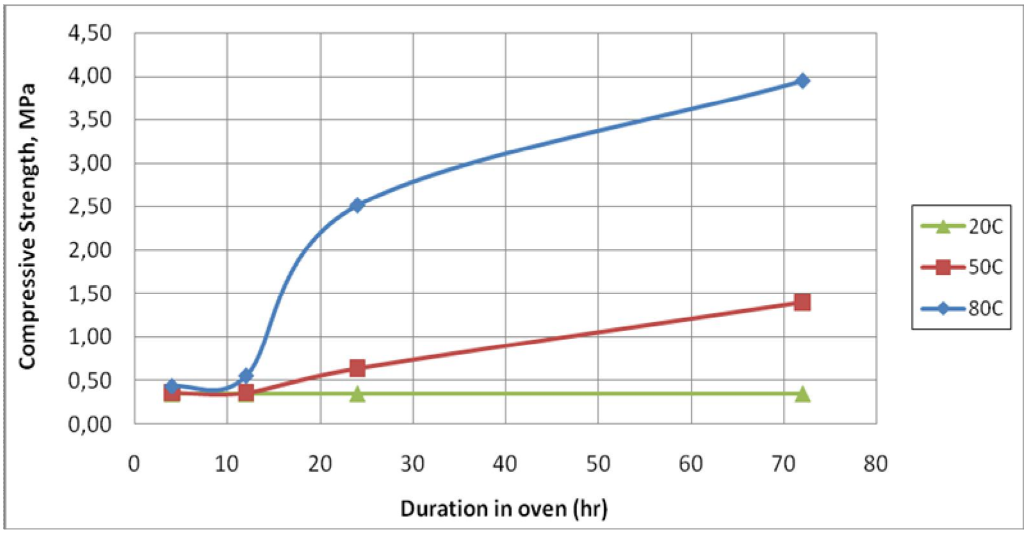

Figure A.69 "28th day Compressive Strength of GF15 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

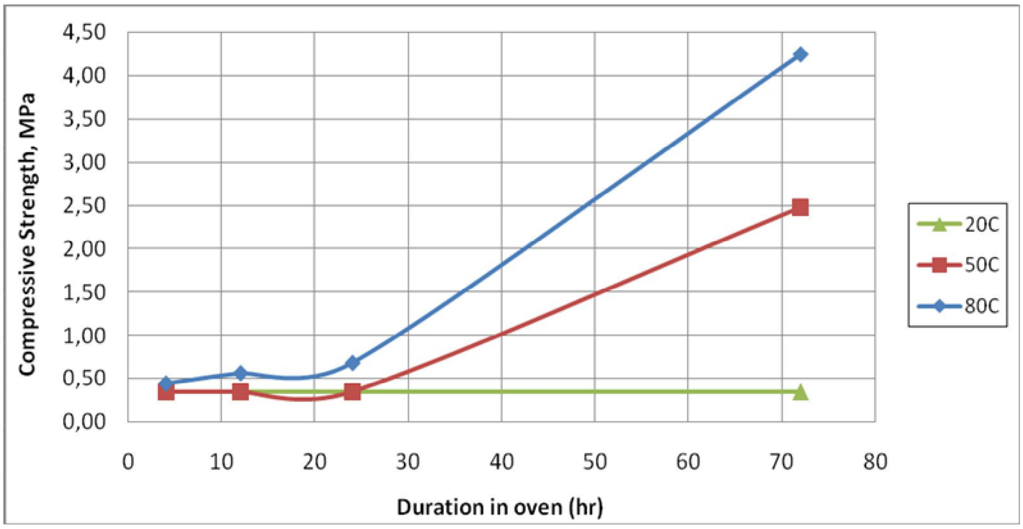

Figure A.70 "7th day Compressive Strength of GF30 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

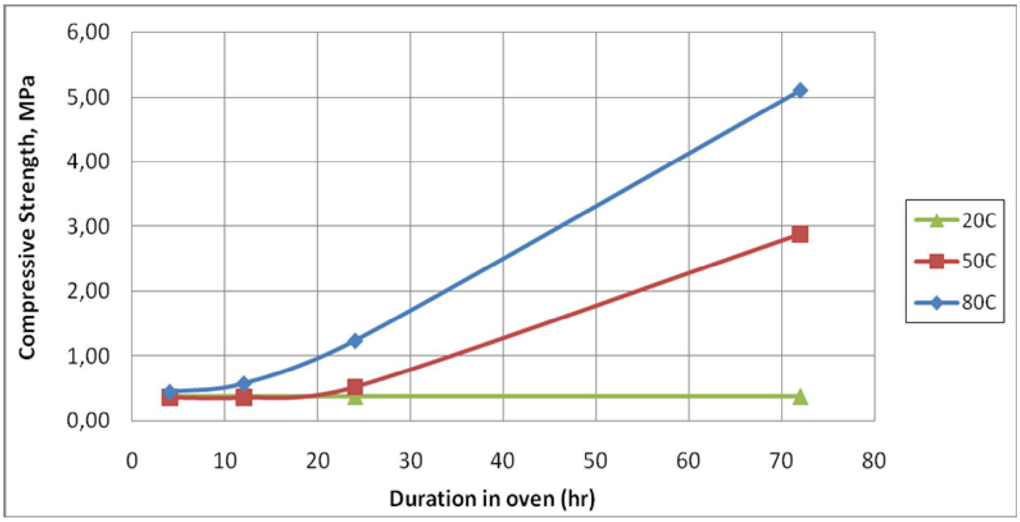

Figure A.71 “14th day Compressive Strength of GF30 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

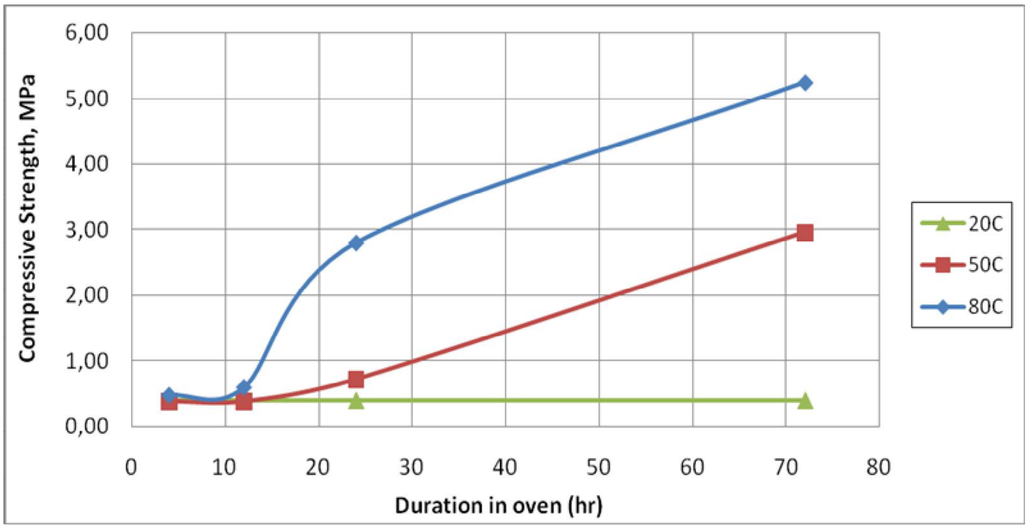

Figure A.72 “28th day Compressive Strength of GF30 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

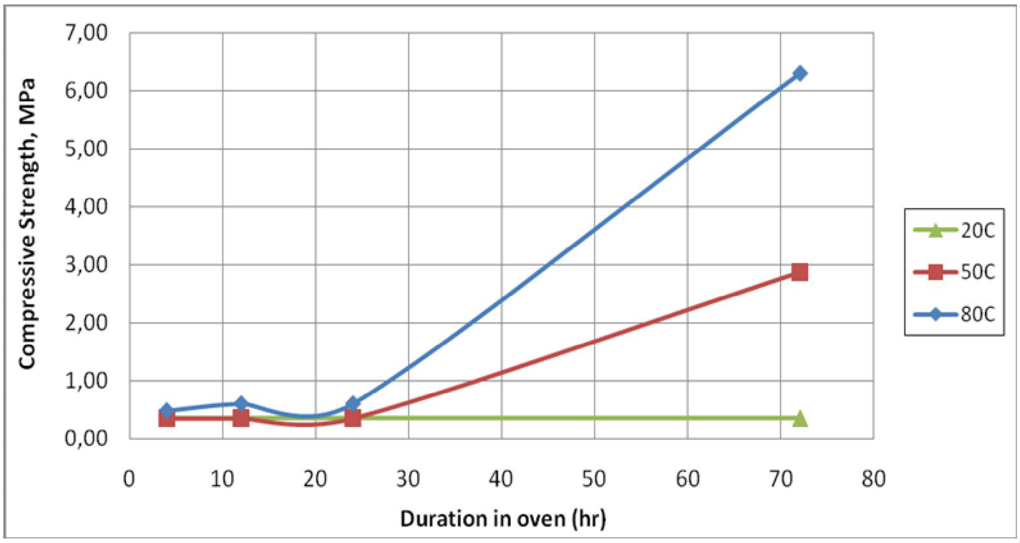

Figure A.73 “7th day Compressive Strength of GF45 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

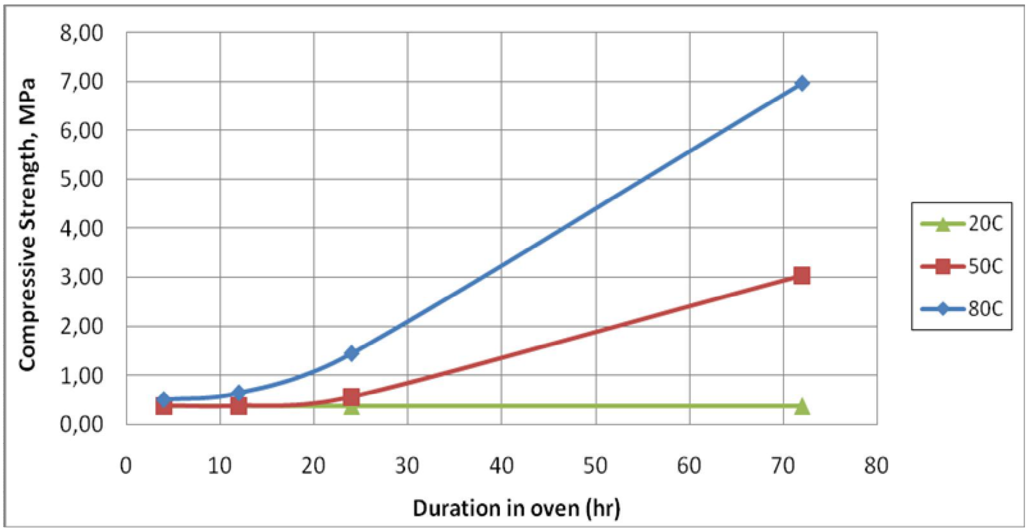

Figure A.74 “14th day Compressive Strength of GF45 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

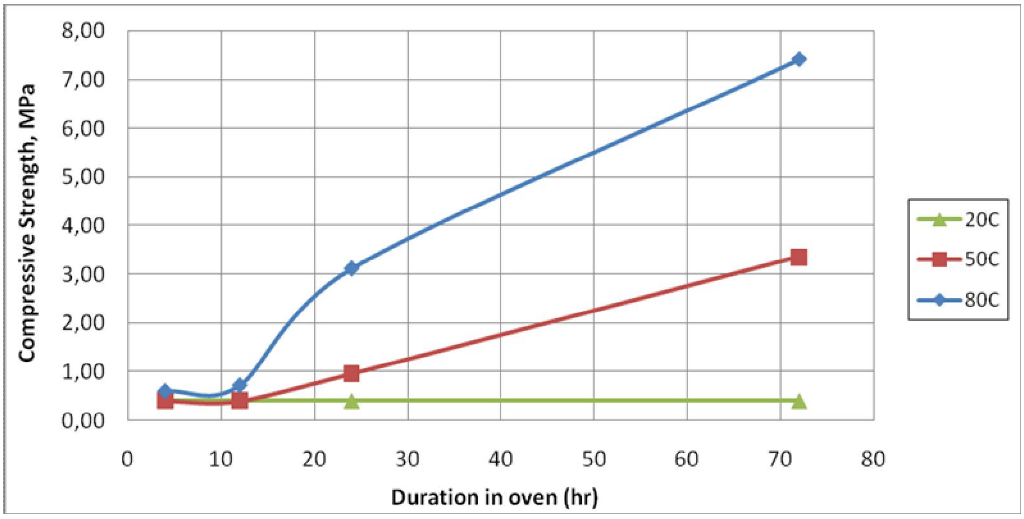

Figure A.75 "28th day Compressive Strength of GF45 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

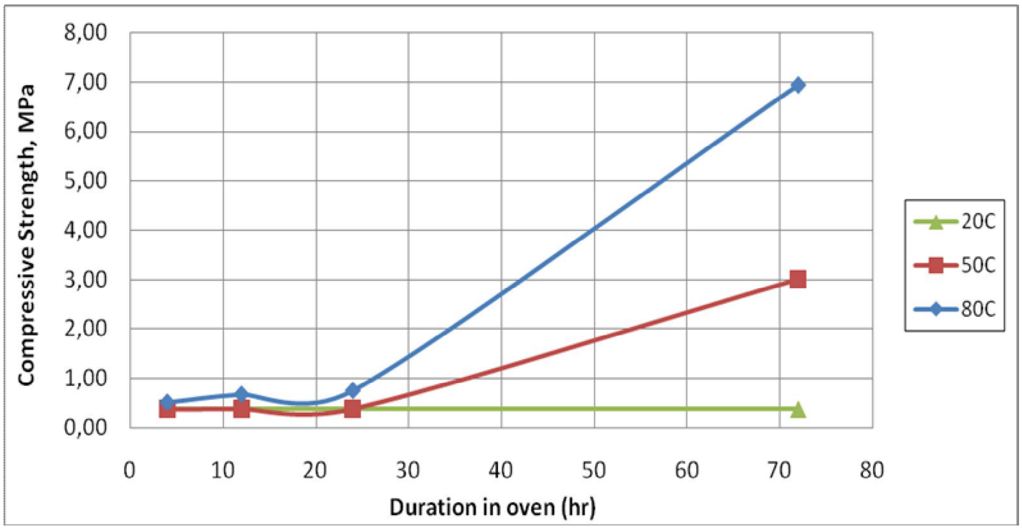

Figure A.76 "7th day Compressive Strength of GF60 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

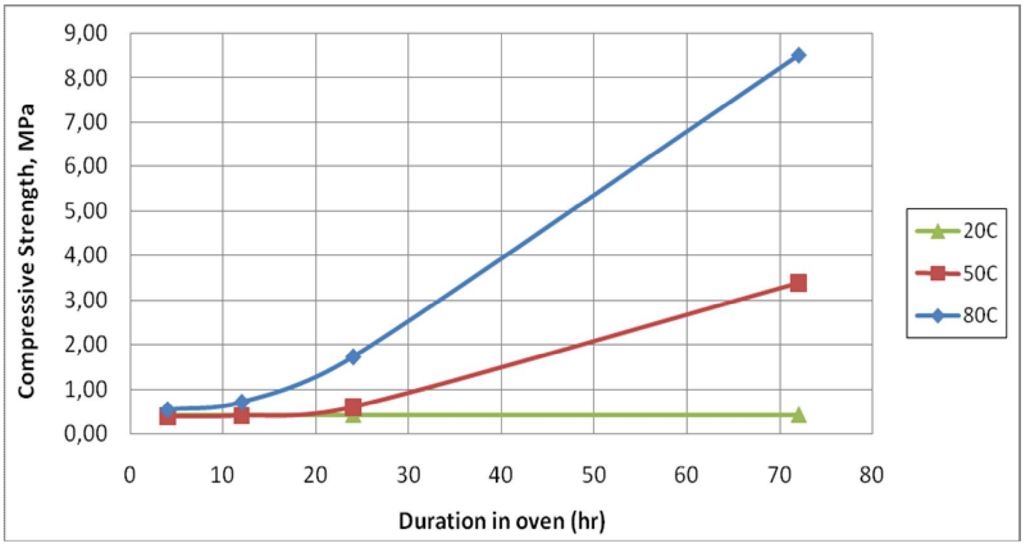

Figure A.77 “14th day Compressive Strength of GF60 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

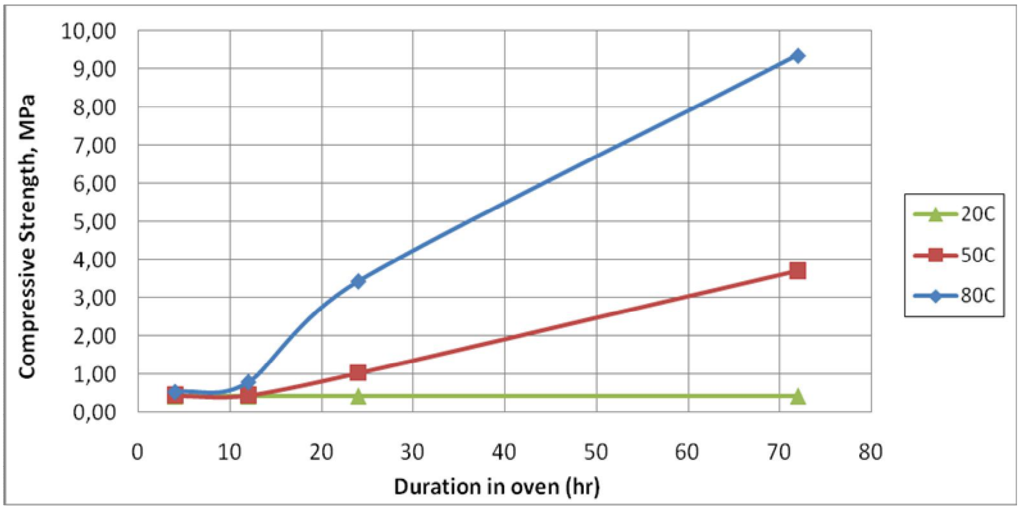

Figure A.78 “28th day Compressive Strength of GF60 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

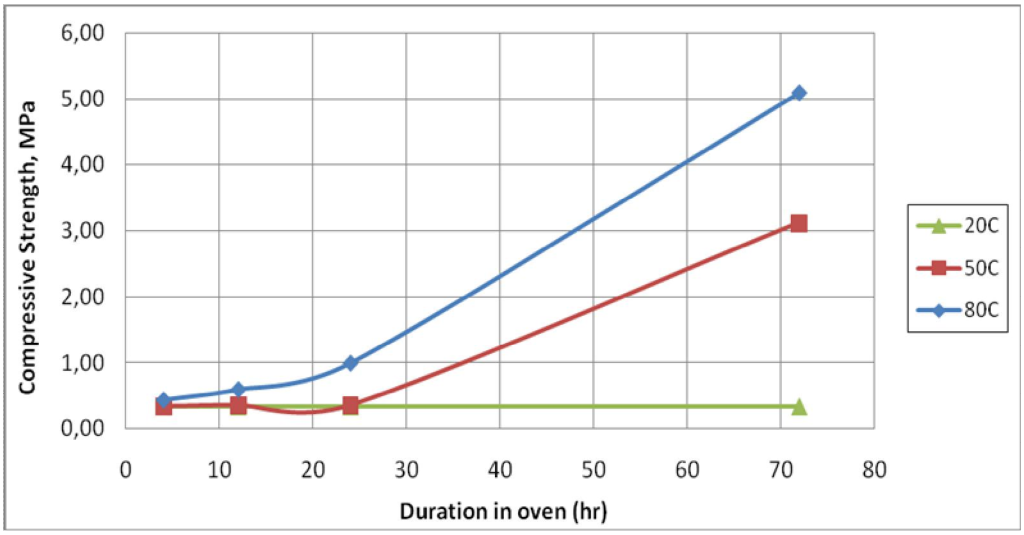

Figure A.79 "7th day Compressive Strength of GF75 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

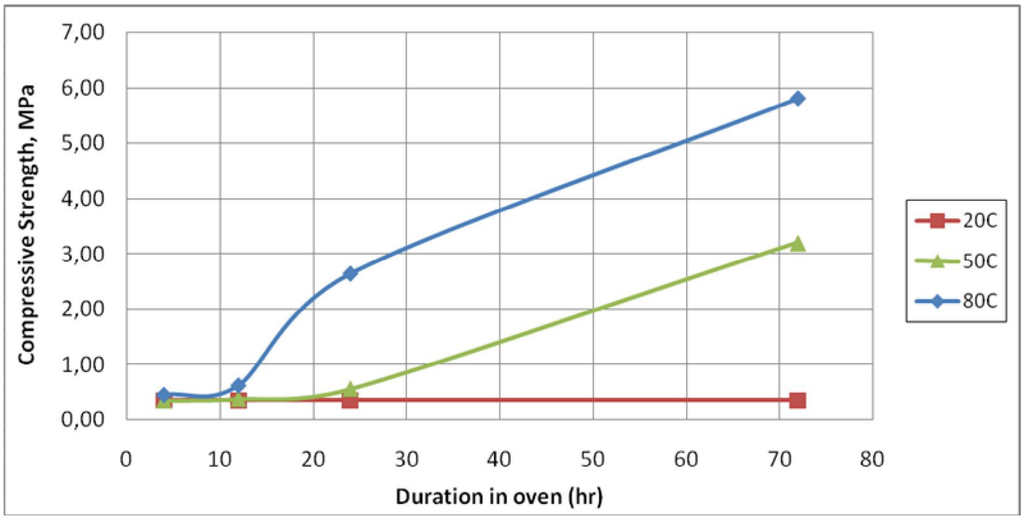

Figure A.80 "14th day Compressive Strength of GF75 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

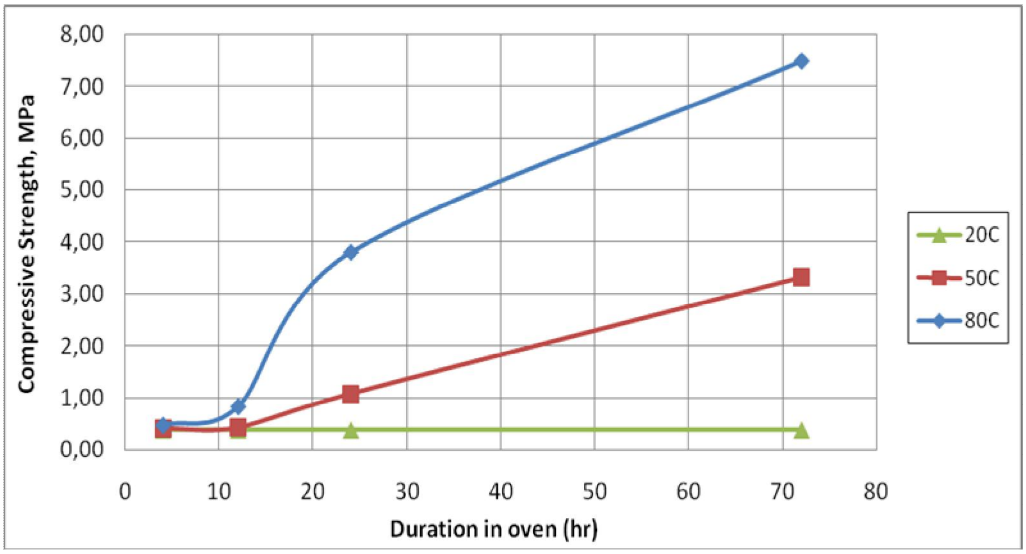

Figure A.81 "28th day Compressive Strength of GF75 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

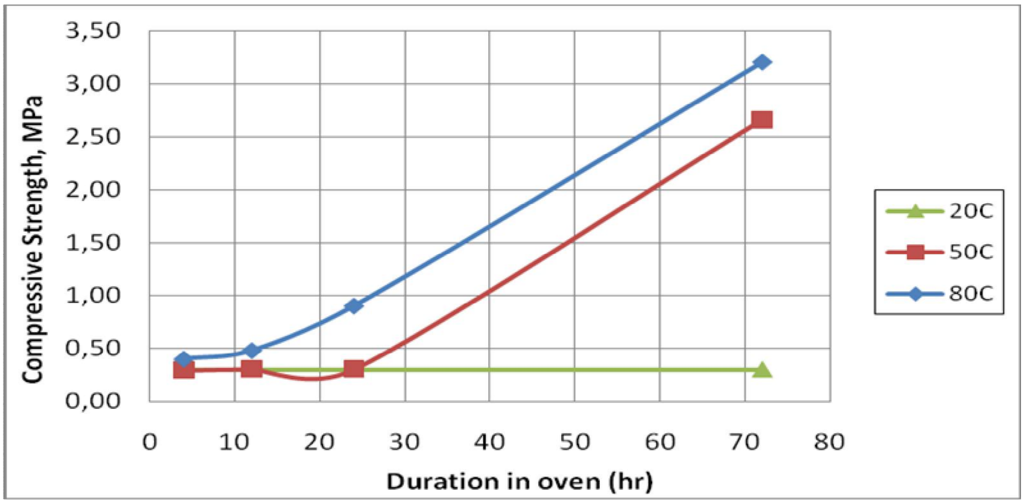

Figure A.82 "7th day Compressive Strength of F Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

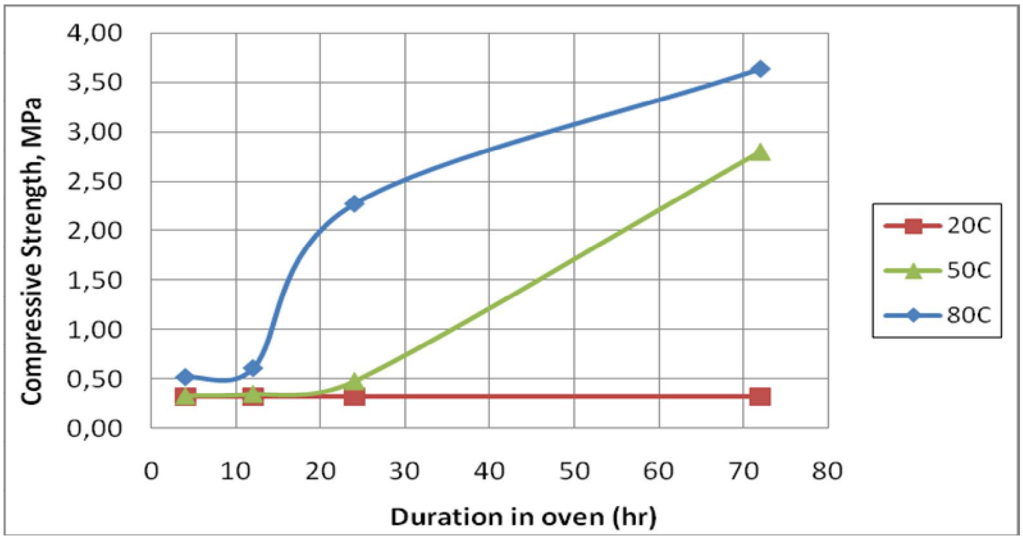

Figure A.83 “14th day Compressive Strength of F Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

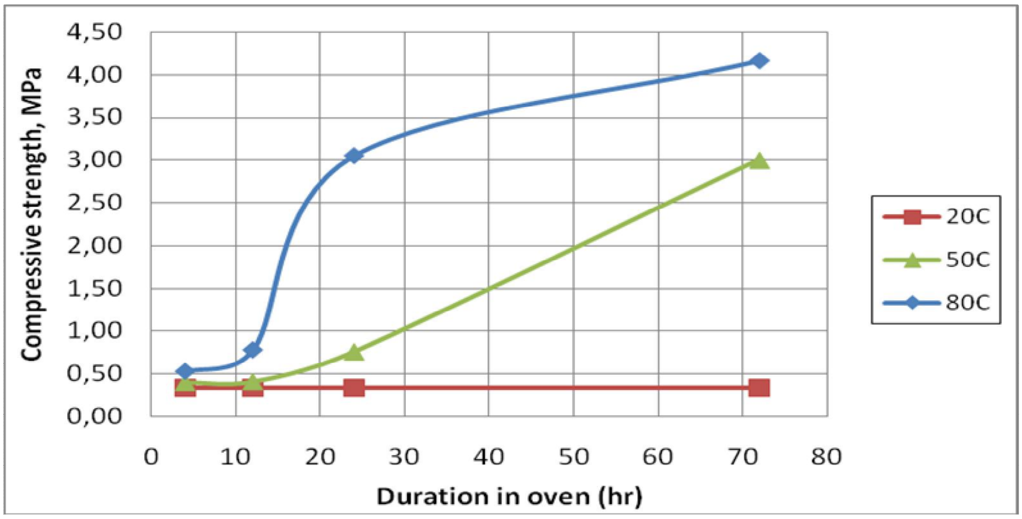

Figure A.84 “28th day Compressive Strength of F Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

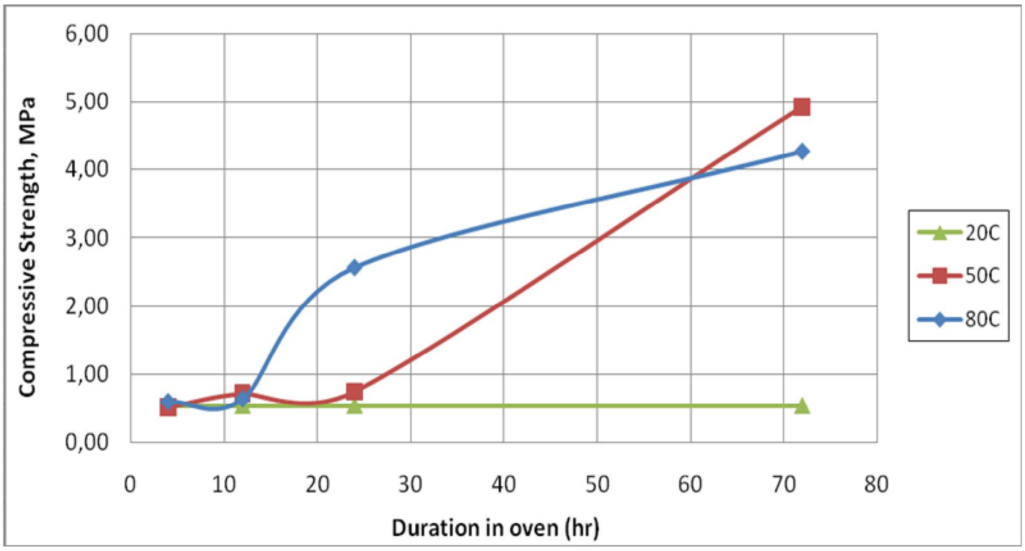

Figure A.85 “7th day Compressive Strength of GS15 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

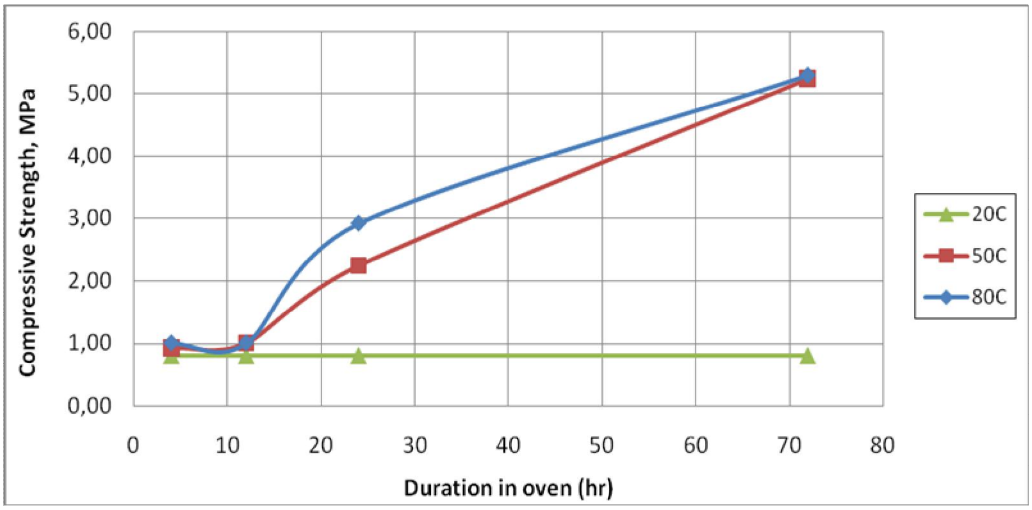

Figure A.86 “14th day Compressive Strength of GS15 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

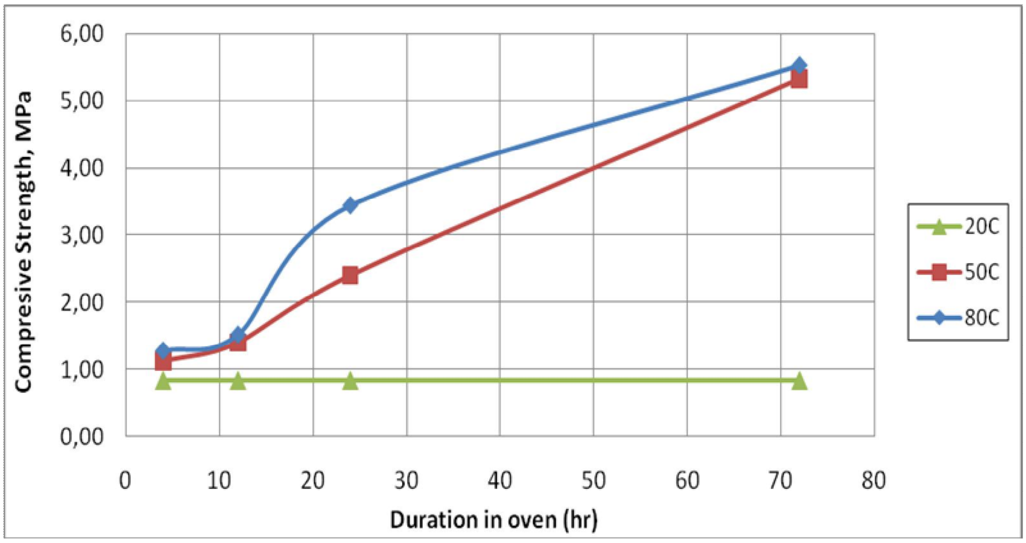

Figure A.87 “28th day Compressive Strength of GS15 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

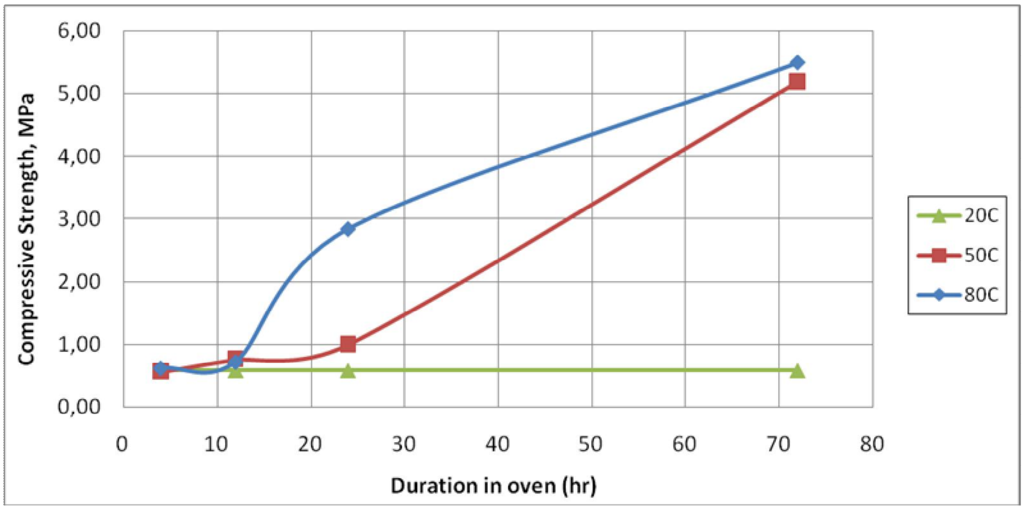

Figure A.88 “7th day Compressive Strength of GS30 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

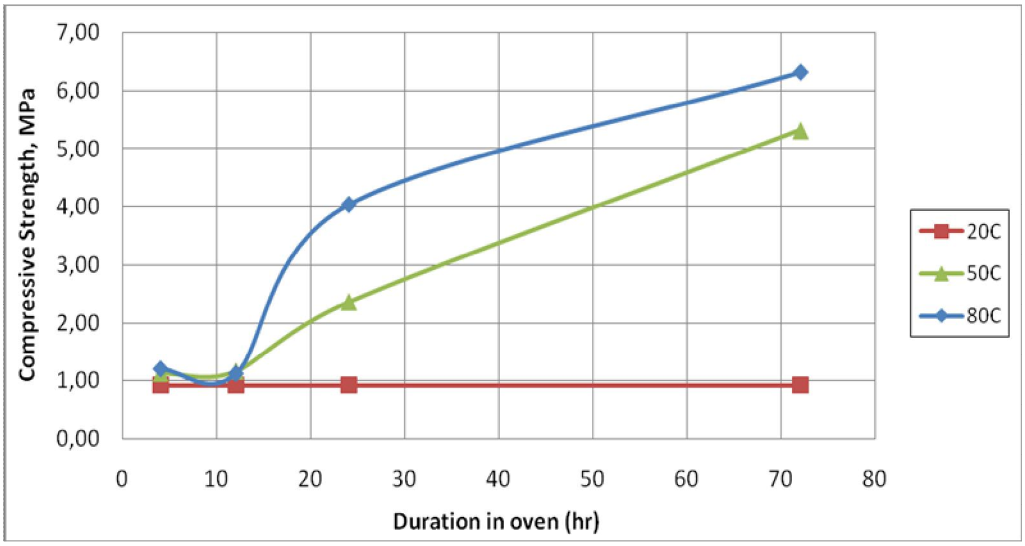

Figure A.89 “14th day Compressive Strength of GS30 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

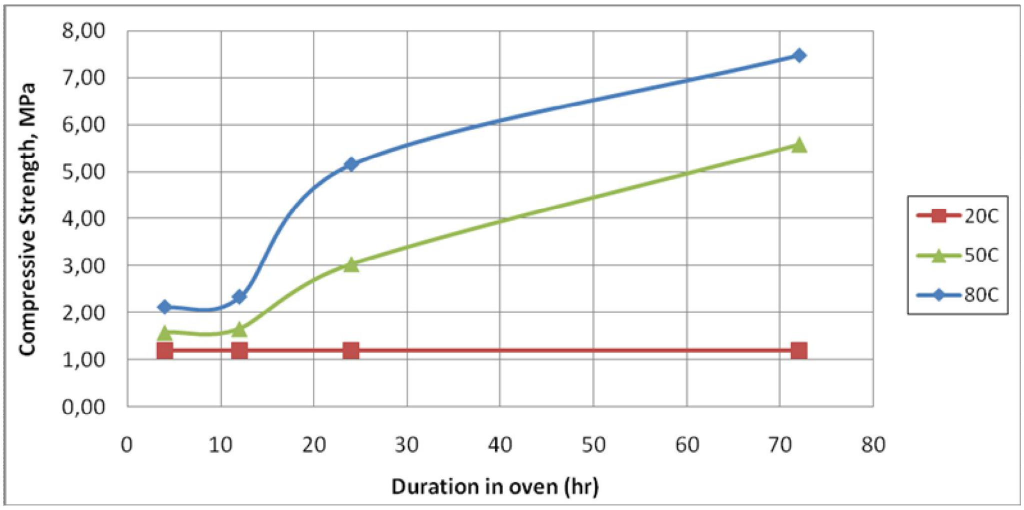

Figure A.90 “28th day Compressive Strength of GS30 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

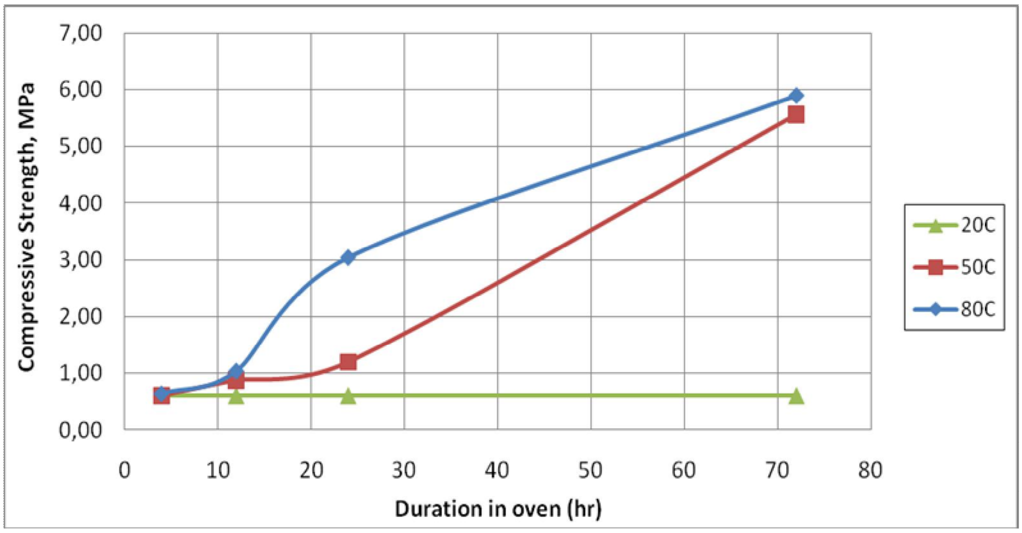

Figure A.91 "7th day Compressive Strength of GS45 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

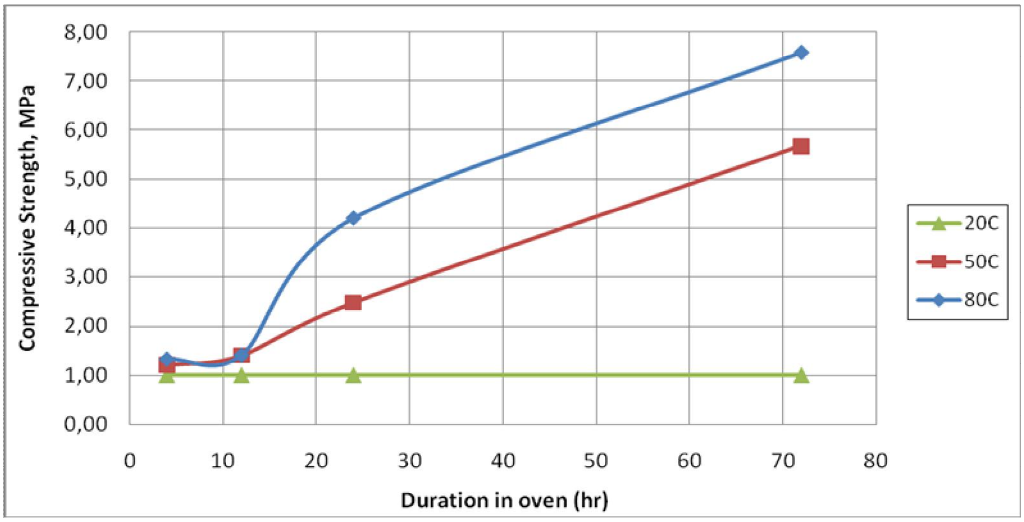

Figure A.92 "14th day Compressive Strength of GS45 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

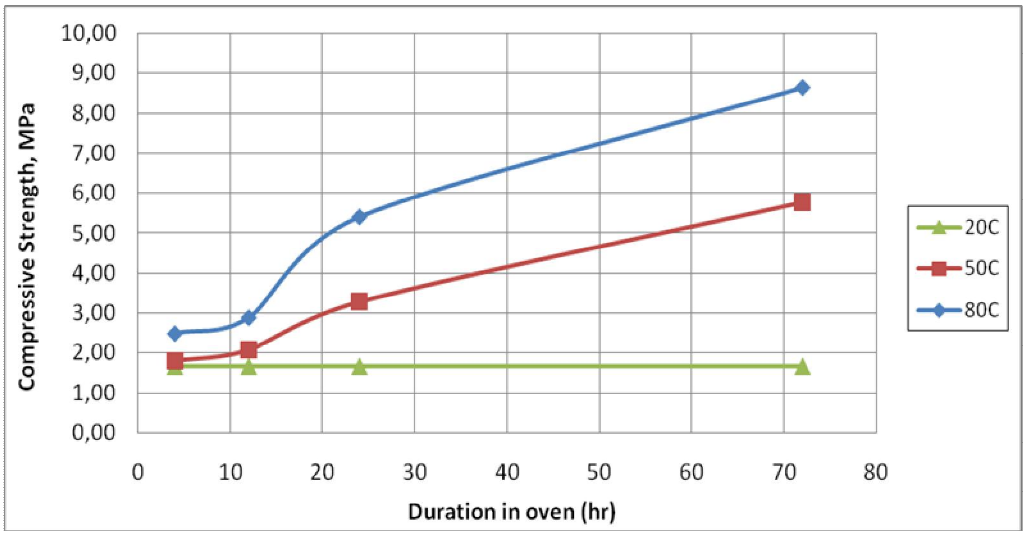

Figure A.93 “28th day Compressive Strength of GS45 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

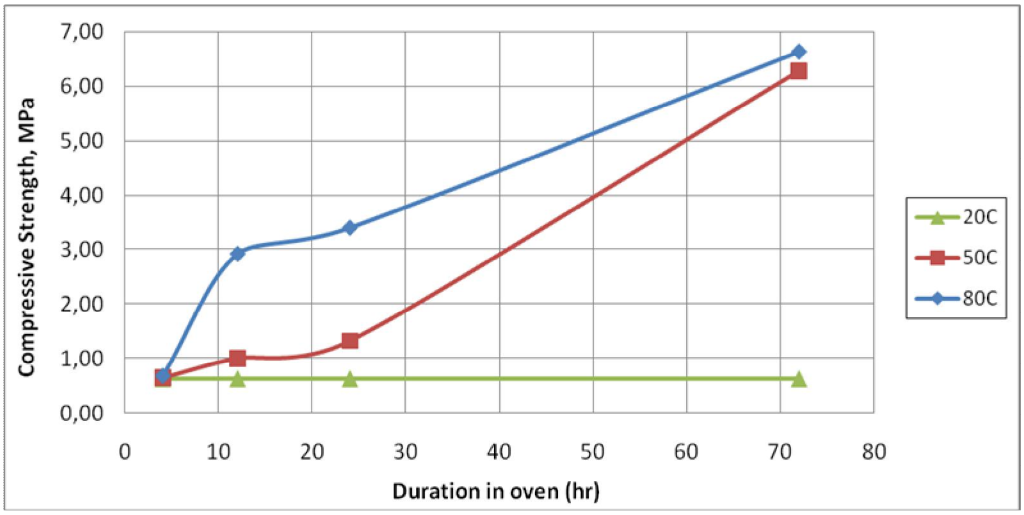

Figure A.94 “7th day Compressive Strength of GS60 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

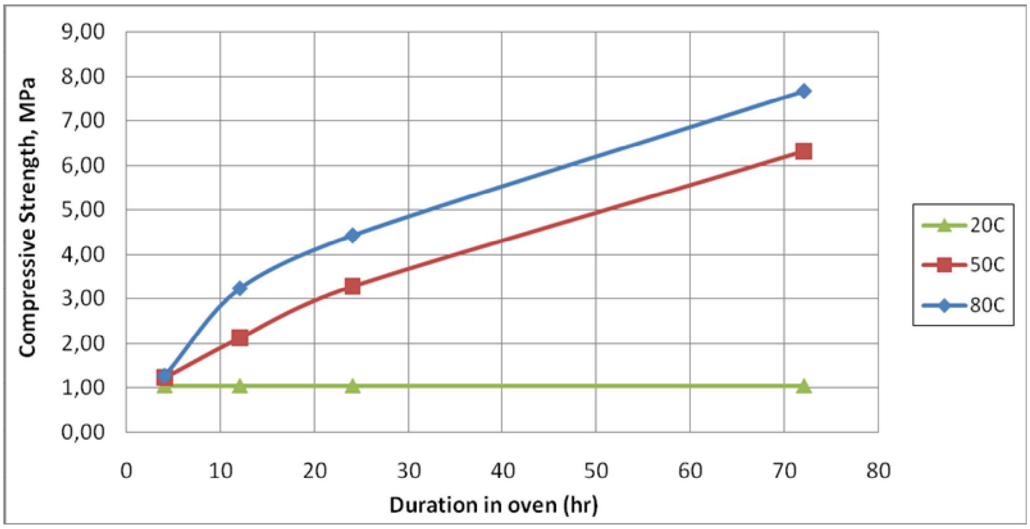

Figure A.95 "14th day Compressive Strength of GS60 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

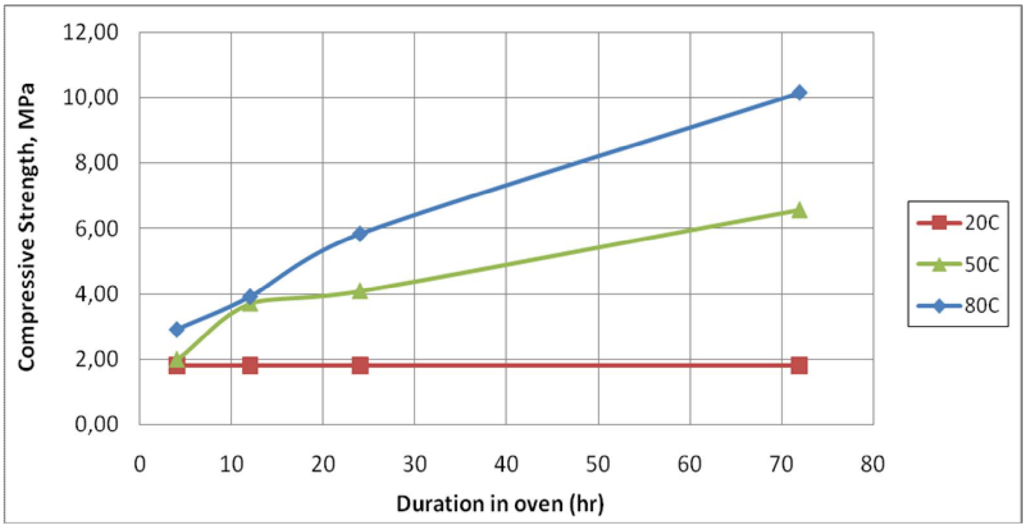

Figure A.96 "28th day Compressive Strength of GS60 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

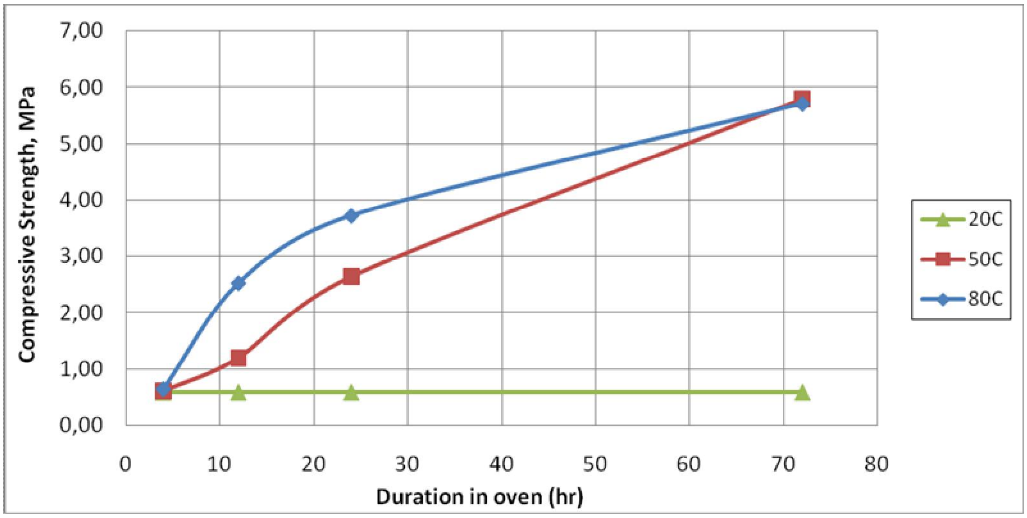

Figure A.97 “7th day Compressive Strength of GS75 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

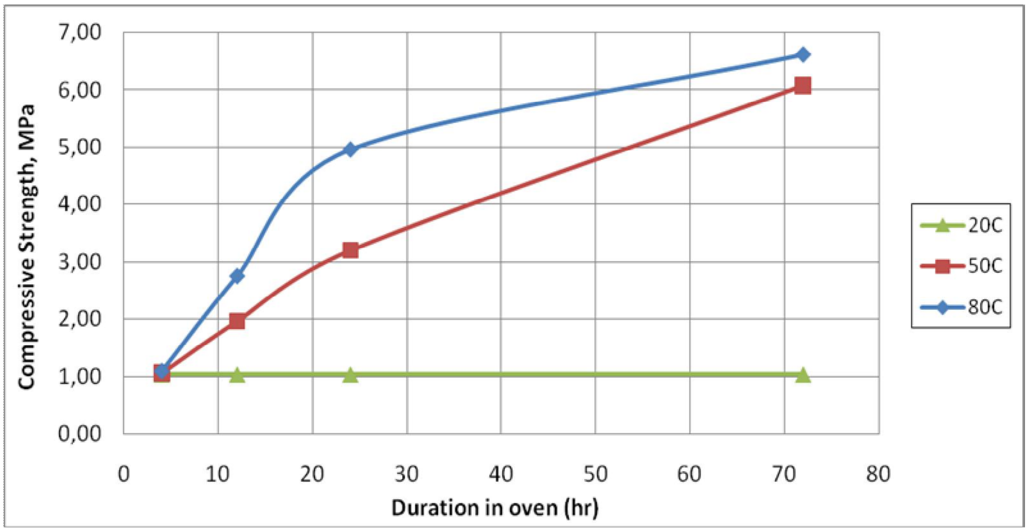

Figure A.98 “14th day Compressive Strength of GS75 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

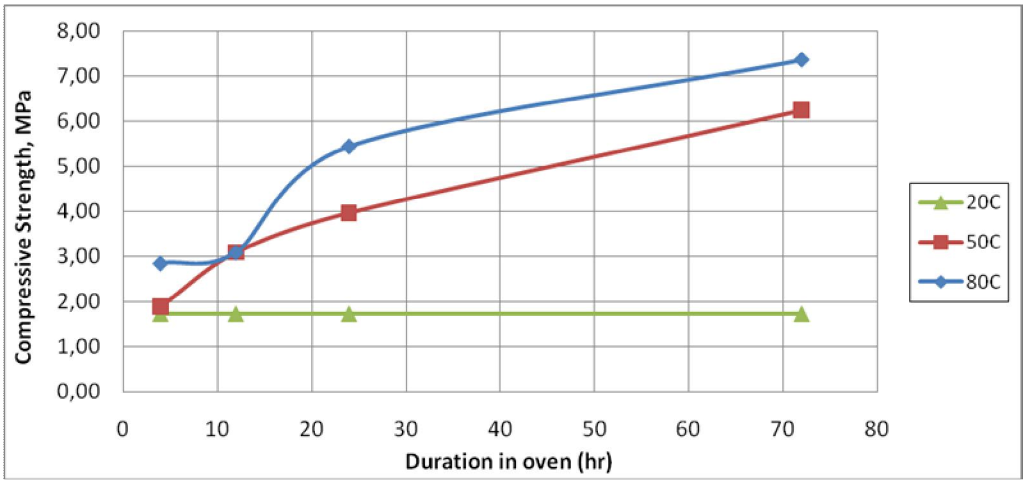

Figure A.99 "28th day Compressive Strength of GS75 Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

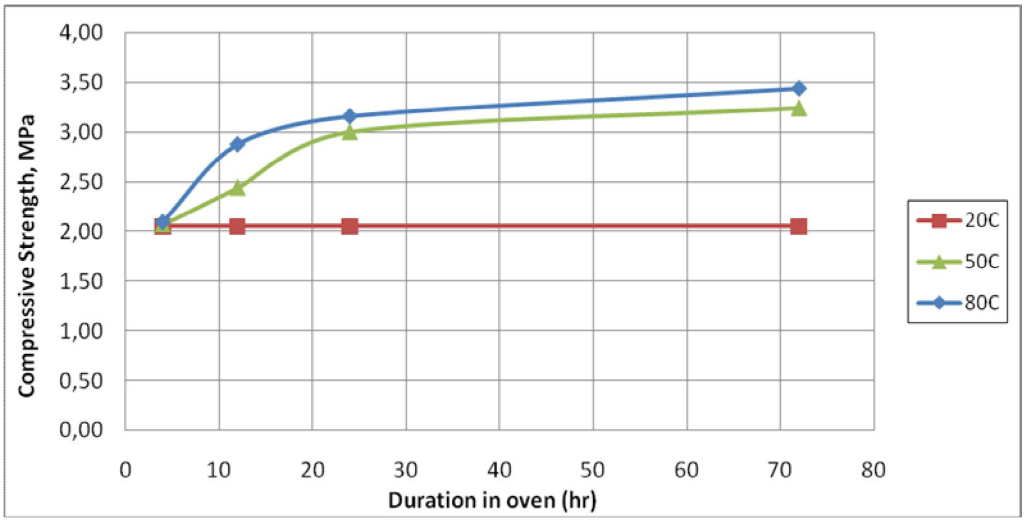

Figure A.100 "7th day Compressive Strength of S Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven" Relationships for Different Temperatures in Oven

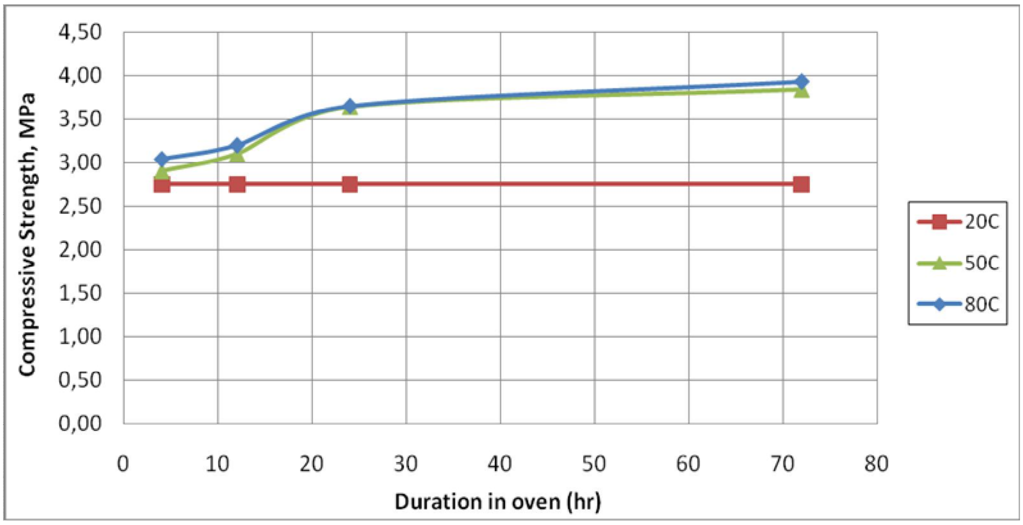

Figure A.101 “14th day Compressive Strength of S Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

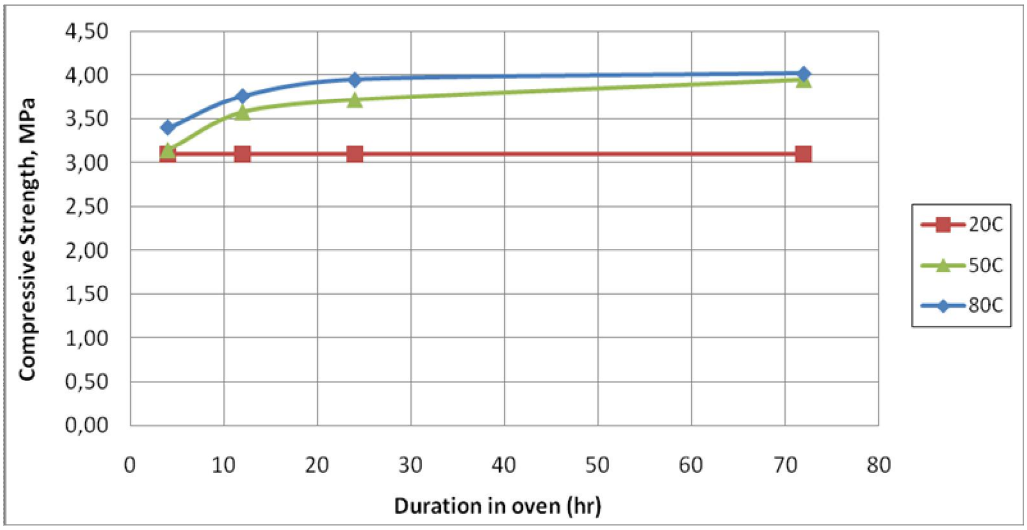

Figure A.102 “28th day Compressive Strength of S Cured in Oven for a While, Then Cured in Water at 20 ^{0}C vs. Duration in Oven” Relationships for Different Temperatures in Oven

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Publications

- Cengiz O., Comparative Evaluation of Steel Mesh, Steel Fiber and High Performance Polypropylene Fiber-Reinforced Shotcrete/Concrete in Panel Test, *M.S. Thesis*, Middle East Technical University, 2001.

- Cengiz O., Turanlı L., Comparative Evaluation of Steel Mesh, Steel Fiber and High-Performance Polypropylene Fiber Reinforced Shotcrete in Panel Test, *Cement and Concrete Research*, Vol. 34, Iss.8, August 2004, pp. 1357-1364.