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An Experimental Study on Separately Ground and together Grinding Portland Slag Cements Strength Properties

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Abstract

In this experimental study 7 and 28 day compressive, flexural strength and slag activity indices of Portland cement control and Portland slag cement were determined experimentally. The results of this study showed that the grinding time required for slag particles are higher than portland cement clinker particles for all the tested Blaine fineness values; therefore, the grind ability of the slag is observed to be lower than the grind ability of the clinker. The results indicated that the increasing the Blaine fineness values of the mortar mixes improved both the 7-day and 28-day slag activity indices. This means that in order to increase the quality of the slag, the granulated blast furnace slag particles should be ground to much finer. Together grinding Portland slag cements show higher strength values than the separately ground ones for the Blaine fineness values of 3000 cm^2/g and 3500 cm^2/g at 2 and 7 days. However, for Blaine fineness values of 4000 cm^2/g and 4500 cm^2/g, the separately ground Portland slag cements have higher strength values than the Together grinding ones at 2 and 7 days. For 28 days, the flexural strength of the Together grinding Portland slag cements show more or less the same values with the separately ground ones for all of the Blaine fineness values. Finally, the flexural strength of the separately ground Portland slag cements show higher values than the Together grinding ones again for all of the Blaine fineness values at 90 days.

Keywords: Granulated blast furnace slag, portland slag cement, together and separate grinding

Introduction

There are two alternatives in manufacturing Portland slag cements and blast furnace slag cements called the Together grinding method and the separate grinding method. In the Together grinding method, Portland cement clinker and granulated blast furnace slag are mixed and ground in the mill whereas in the separate grinding method Portland cement clinker and granulated blast furnace slag are ground separately in the mill and then mixed together. After the grinding operation is finished, for both methods 3-6 % gypsum mineral is used as a set retarder[2].

Historically, Portland slag cement has been produced using the Together grinding method. In this process, granulated blast furnace slag with the Portland cement clinker and gypsum are ground together in the tube mills. Although this method is less energy demanding than the separate grinding method[8], the main drawback of this method is that the particle size distributions of the slag and clinker materials are different[9]. This phenomenon was explained by the fact that hardness of granulated blast furnace slag is higher than clinker so that clinker particles are usually ground more easily than the granulated blast furnace slag particles and they show additional abrasive effect to the clinker particles[10]. Unfortunately, this is not the treatment required for the optimum performance of slag.

On the other hand, another scientific study has shown that Together grinding of granulated blast furnace slag and Portland cement clinker consumes more energy than separate grinding to reach 3500 cm^2/g Blaine fineness. However, the lower energy consuming separately ground Portland slag cement with 25% by weight of granulated blast furnace slag shows lower strength values than higher energy consuming Together grinding Portland slag cement. This situation is explained by the fact that Together grinding provides more homogeneous product and particle size distributions of the separately ground and Together grinding Portland slag cements are not same [11]. The consumed energies of separately ground cements were calculated by weighted average of consumed energies of the ingredients to reach 3500 cm^2/g . All these cements have the same Blaine fineness (3500 cm^2/g ± 100 cm^2/g). Strengths of separately ground cements and were given as percentage of the strengths of Together grinding cement of the same composition at the same age. Although granulated blast furnace slag cements are known as produced by grinding granulated blast furnace slag together with Portland cement clinker and a small amount of gypsum, recent studies on separate grinding concluded that separate grinding should be preferred in view of lower specific energy consumption, ease of manufacture, higher addition of slag (i.e. fewer environmental hazards) on top of higher flexibility in product quality arrangement according to market requirements [12]. In order to prove these properties, Öner [13] compared separate grinding and together grinding of granulated blast furnace slag cements with respect to their grindabilities, grinding kinetics and strength properties. Firstly, he concluded that the grindability of the slag is lower than clinker; slag is more resistant to grinding. Secondly, grindability of the mixture is not the weighted average of the component grindabilities but is even lower than the harder component slag[12]. This indicates that the specific grinding energy per specific surface necessary to produce blast furnace slag cement is greater when the components are together grinding[13]. Thirdly, he argued that when grindabilities of the components are different, their individual distributions are also different. The harder component, slag, tends to accumulate in coarse fractions having narrower size distribution, higher mean size and lower specific surface area and the softer component, clinker, being ground at a higher rate would accumulate in finer size fractions having a wider size distribution, lower mean size and higher specific surface area[13]. Because of these results, although the specific surface areas of the two blast furnace slag cements are the same, the slag in the interground blast furnace slag cement is relatively coarser than the slag ground separately. As the coarser slag would not take part in hydration reaction as fast as the fine slag, the compressive strength values of the blast furnace slag cement produced by Together grinding is lower than separately ground blast furnace slag cements, but no improvement has been seen for flexural strengths[13].

Separate grinding of ground granulated blast-furnace slag and Portland cement, with materials combined at the mixer, has two advantages over the Together grinding blended cements; i. Each material can be ground to its own optimum fineness, ii. The proportions can be adjusted to suit the particular project needs[13].

Öner et al.[12] investigated the strength development of 1:1 mixes of clinker and granulated blast furnace slag with varying fineness of components from 3000 to 6000 cm^2/g Blaine. Overall results indicated that in manufacturing blended cements, it is not only the fineness of the clinker-slag mix but also of the individual components which govern the choice of the mix composition for a desired strength. Moreover, initial setting times for blast furnace slag cements are higher than the initial setting time of the control cement. Finally, in manufacturing blast furnace slag cement, grinding the clinker component to a higher fineness should be practiced, as it is more effective in regulating the strength and it is also more cost-effective clinker grinding is less energy consuming than grinding slag as expressed by shorter grinding times required for the same fineness levels[12].

Another study was done by Binici et al.[14] about the effect of particle size distribution on the properties of blended cements incorporating granulated blast furnace slag and natural pozzolan. Pure Portland cement, natural pozzolan and granulated blast furnace slag were used to obtain blended cements containing 10, 20 and 30 % additives. The cements were produced by together grinding and separate grinding and then blending. Each group had two different finenesses of 280 m^2/kg and 480 m2/kg Blaine. According to the particle size distribution curves, the separately ground finer specimens, which had the highest compressive strength and sulfate resistance, had the highest percent passing for every sieve size[14]. They also observed that the compressive strength of all the blended cements was found to be higher than the minimum value stated by TS EN 197-1[3]. Moreover, the average compressive strength of the separately ground blended cement specimens at 28 days was higher by about 8% than that of the Together grinding ones. Finally, they showed that the strength of the mortars improves with an increase in the Blaine values of the cement[14].

Doğulu[15] studied the effect of fineness of Iskenderun ground granulated blast furnace slag on its cementations' property when used as cement replacing material in Portland cement mortar with testing the 3-, 7-, 28-and 91-day flexural and compressive strengths of the mortars [15]. He used one type of Portland cement and five different fineness values of ground granulated blast furnace slag 3000, 3200, 3700, 3900 and 4400 cm2/g Blaine and three different replacement amounts of 25, 35 and 45 percent of slag by weight of total cementations' material[15]. As a result of this study, he showed that as the fineness of the slag increases, the compressive strength of the mortar also increases. However, the effect of the replacement amount to the strength development of the mortar depends on the time of testing. For the early days, the lower the slag content the higher is the strength development, but for later days (91) the higher the slag content, the higher is the strength development[15].

Hogan and Meusel[16] investigated the properties of granulated blast furnace slag produced by water granulation and they used a 4-by 11-m two-compartment cement grinding mill with the help of the Atlantic Cement company, in New York[16]. They reached some important conclusions which can be summarized as follows: Concrete strength development is slower for slag cement concretes at early ages, generally through three days of age; however, thereafter strengths for slag cement concretes were generally found to be greater, and the ultimate strength is usually significantly greater. Slag cement concretes subjected to elevated temperature (71.1°C) curing exhibited greater strength development than the straight Portland cement concrete at all ages. On the other hand, slag cement concrete strength development is more adversely influenced by cold weather (4.4 °C) conditions than is the strength development of straight Portland cement concrete. Finally they stated that the optimum slag replacement for mortar strength development appears to be 50% replacement[16].

Dubovoy et al.[17] conducted more or less the same study as Hogan and Meusel[16]. They investigated the physical properties of pastes, mortars and concretes with using various granulated blast furnace slag's and slag cement combinations. They have found that for both mortars and concretes, an optimum level of slag replacement exists for which strength is maximized and this level is approximately 50% of slag weight replacement.

Moreover, at normal temperatures, early age strength development is retarded when slag's are used and setting time of pastes is also retarded when a portion of the cement is replaced by slag. Finally, they have stated that strength of slag cement mixtures increases with an increase in slag fineness as it is in at later ages[17].

Öner and Akyüz[18] studied the optimum level of ground granulated blast furnace slag on the compressive strength of concrete. According to their test results, the compressive strength of ground granulated blast furnace slag concrete increases as the granulated blast furnace slag content is increased up to an optimum point about 55-59 %, after which the compressive strength decreases. Furthermore, they concluded that as the ground granulated blast furnace slag content increases, the water to binder ratio decreases for the same workability, and thus, the ground granulated blast furnace slag has positive effects on workability. Finally they stated that the early age strength of ground granulated blast furnace slag concretes was lower than the control concretes with the same binder content, but, as the curing period is extended, the strength increase was higher for the ground granulated blast furnace slag concretes. They explained this conclusion by the fact that the pozzolanic reaction is slow and the formation of calcium hydroxide requires time[18].

Effects of Ground Granulated Blast Furnace Slag on Mortar and Concrete Properties Workability: Concrete containing ground granulated blast furnace slag increases the workability and placeability since the total volume of the fine particles become higher when compared with concrete not containing ground granulated blast furnace slag[5]. Moreover, it is also stated that the static electric charges of slag particles are much lower than those of the cement particles and this results in an easier dispersion in the mixture[4]. Finally, Fulton[19] investigated in detail the effect of ground granulated blast furnace slag on workability and he stated that cementations' matrix containing ground granulated blast furnace slags exhibited greater workability due to the increased paste content and increased viscosity of the paste.

Setting Time: When ground granulated blast furnace slag is used as a replacement for part of the Portland cement in concrete mixtures, an increase in time of setting can be expected[5]. Fulton[19] stated that the time of setting is dependent on the initial curing temperature of the concrete, the proportion of the blend used, the water to cement plus slag ratio, and the characteristics of the Portland cement.

Strength and Strength Gain: Hogan and Meusel[16] claimed that the compressive and flexural strength gain characteristics of concrete containing ground granulated blast furnace slag can vary over a wide range. Use of Grade 120 slag typically imparts reduced strength at early ages (1 to 3 days) and increased at later ages (7 days and beyond) compared to Portland cement concrete[5]. Generally, the strength of concrete containing ground granulated blast furnace slag depends on the water to cementations' material ratio, physical and chemical characteristics of the Portland cement, and curing conditions [5]. Hogan and Meusel stated that the optimum blend of ground granulated blast furnace slag should be 50 % of the total cementations' material[16].

Material and Methods

Materials Used in the Study: One type of Portland cement clinker, one type of gypsum mineral and one type of granulated blast furnace slag were used to prepare the cements used in this study. The types of tests performed on these materials and the relevant test standards are given in table 1.

Table-1
Tests Performed on Portland cement Clinker and Granulated Blast Furnace Slag

Relevant Standard	Tests Performed on Portland Cement Clinker and Granulated Blast Furnace Slag
TS EN 197-1 [3]	Chemical Analysis (X-Ray Fluorescence)
ASTM C 204 [20]	Fineness by Blaine Air Permeability
ASTM C 188 [21]	Density

Portland cement Clinker and Gypsum Mineral: For the production of cements, the Portland cement clinker of Set Cement from the Sofyan-Tabriz Plant was chosen. The clinker was first dried at a temperature of 100°C in the oven and then crushed before grinding operation to eliminate the very large particles. Like Portland cement clinker, the gypsum mineral was also obtained from the Set Cement Sofyan-Tabriz Plant and dried at a temperature of 60°C and crushed before feeding to the ball mill. For all cements produced, the gypsum/clinker ratio was 3.5/96.5 by weight. The results of the chemical analysis of the Portland cement clinker are shown in table 2.

Table-2
Chemical Composition of the Portland cement Clinker

Portland Cement Clinker, %	Oxides
21.07	SiO_2
5.85	Al_2O_3
4.35	Fe_2O_3
64.13	CaO
2.03	MgO
0.94	Na_2O
0.87	K_2O
0.78	SO_3

The main compounds of the Portland cement clinker used in the study were calculated by using Bogue's Equation[1] and shown in table 3.

Table-3
Compound Composition of the Portland cement Clinker Compound Content (%)

Compound	Content (%)
C_3S	53.22
C_2S	20.25
C_3A	8.14
C_4AF	13.24

Granulated Blast Furnace Slag: The granulated blast furnace slag used in this research was supplied and produced by Set cement Sofyan-Tabriz factory. The chemical composition of the granulated blast furnace slag is shown in table-4.

Table -4
Chemical Composition of the Granulated Blast Furnace Slag

Granulated Blast Furnace Slag, %	Oxides
33.85	SiO_2
18.33	Al_2O_3
2.95	Fe_2O3
33.71	CaO
9.47	MgO
-	Na_2O
0.82	K_2O
0.87	SO_3

Standard Sand: Standard Rilem-Cembureau type sand, relevant to the TS EN 196-1[22] was used in the preparation of all the mortars and pastes.

Water: The water used in this study was regular tap water in the construction materials laboratory which is connected to the campus water network system at Tabriz.

Experimental Program: The experimental program of this study is composed of five major sections: i. Determination of general chemical, physical and mechanical characteristics of the raw materials according to the related TS EN and ASTM standards, ii. Determination of the slag activity indices of the slag's having different Blaine fineness values in accordance with ASTM C 989[7], iii. Determination of the effect of separate grinding of Portland cement clinker, gypsum and granulated blast furnace slag with different Blaine fineness values normal as such mortars cement slag Portland of properties various on consistency, time of setting, flexural and compressive strengths in accordance with ASTM C 187[23], ASTM C 191[24], TS EN 196-1[22], respectively, iv. Determination of the effect of Together grinding of Portland cement clinker and granulated blast furnace slag with different Blaine fineness values on various properties of Portland slag cement mortars such as normal consistency, time of setting, flexural and compressive strengths in accordance with ASTM C187[23], ASTM C191[24], TS EN 196-1[22], respectively, v. Determination of the various properties of Portland cement such as normal consistency, time of setting, flexural and compressive strength with different Blaine fineness values in accordance with ASTM C187[23], ASTM C191[24], TS EN 196-1[22], respectively.

Grinding of the Materials: Before the production of the Portland slag cements, the materials, Portland cement clinker, gypsum and granulated blast furnace slag had to be ground to the target Blaine fineness values by using separate grinding and together grinding methods. For this purpose, Portland cement clinker and gypsum mineral were crushed to 0.5 to 1 cm by the laboratory type jaw crusher before feeding to the ball mill in order to eliminate the very large particles. Since the granulated blast furnace slag was fine enough for grinding operation it was not necessary to crush them in the jaw crusher. Grinding of all the materials to the desired Blaine finenesses was done by a laboratory type ball mill that was 460 mm in length and 400 mm in diameter and the revolution rate was 30 revolutions per minute. The grinding medium were both balls and cylpebs; having bulk densities of around 4650 kg/m^3 and 4700 kg/m^3, respectively. The sizes of the balls and cylpebs were selected small in size, ranging from 30 to 70 mm and 10 to 30 mm, respectively, in order to reach the high Blaine fineness values of the materials.

The Size Distribution of the Grinding Medium: The ball mill feed was selected as 10 kg for Portland cement clinker and granulated blast furnace slag in the separate grinding operation, and 10 kg for Portland cement clinker (70 % by weight) and granulated blast furnace slag (30 % by weight) mixture in the Together grinding operation. Gypsum was ground separately in the ball mill and added to every Portland slag cement mortar and paste in appropriate amounts so as to obtain 4 % gypsum in the mixture.

During the grinding operation, after the first 30 minutes the machine was stopped and a sample of about 70 g was taken in order to determine the specific gravity of the material using ASTM C 188[21]. After this determination grinding was continued stopping the ball mill from time to time and taking a 10 g of sample in order to determine the target Blaine fineness values by using ASTM C 204[20].

Finally, 21different types of ground product were successfully produced from the ball mill grinding which are tabulated in table 5. In all produced Portland cements and Portland slag cements, Blaine values in ±100 cm^2/g sensitivity were accepted as nominal.

In order to understand the difference on the particles in the separate grinding and together grinding operations, particle size distribution of the Portland cement clinker and ground granulated blast furnace slag was determined by using a laser diffraction particle size analyzer which is the most efficient way of determining particle sizes over a wide range. The particle size distribution of each material are plotted on log-log graph papers in appendix B using Rosin-Rammler-Bennett distribution function (equation 1) which is one of the most frequently used particle size distribution model in the cement industry. The equation of the Rosin-Rammler-Bennett distribution is

Y = {1-exp [-(d/k) n]} (1)

Where Y is the cumulative weight percent undersize, d is the particle size, in m, k is the size modulus and n is the distribution modulus[25].

Table-5
Grinding Details of the Materials

Material	Exact Blaine Fineness (cm^2/g)	Assumed Blaine Fineness (cm^2/g)
Clinker (40 kg)	3010	3000
Clinker (40 kg)	3860	3500
Clinker (40kg)	4120	4000
Clinker (40kg)	4740	4500
Slag (40 kg)	3100	3000
Slag (40 kg)	3530	3500
Slag (40 kg)	3990	4000
Slag (40 kg)	4600	4500
Clinker (9 kg) + Slag (1 kg)	3130	3000
Clinker (8 kg) + Slag (2 kg)	3080	3000
Clinker (7 kg) + Slag (3kg)	3200	3000
Clinker (9 kg) + Slag (1 kg)	3560	3500
Clinker (8 kg) + Slag (2 kg)	3090	3500
Clinker (7 kg) + Slag (3 kg)	2980	3500
Clinker (9 kg) + Slag (1 kg)	4100	4000
Clinker (8 kg) + Slag (2 kg)	4070	4000
Clinker (7 kg) + Slag (3 kg)	4030	4000
Clinker (9 kg) + Slag (1 kg)	4590	4500
Clinker (8 kg) + Slag (2 kg)	4620	4500
Clinker (7 kg) + Slag (3 kg)	4510	4500
Gypsum (10 kg)	6380	6300

Preparation of the Portland Slag Cements: For the production of the Portland slag cements, ground granulated blast furnace slag was used as partial replacement of Portland cement clinker at 10,20,30 percent by weight in order to obtain CEMII/B-S containing 21-35 % ground granulated blast furnace slag by weight. Since materials were ground by using separate and Together grinding methods to four different Blaine fineness values, namely, 3000 cm^2/g, 3500 cm^2/g, 4000 cm^2/g and 4500 cm^2/g, eight types of Portland slag cements were prepared. For control purposes, with using Portland cement clinker samples having the same Blaine fineness values with the Portland slag cements, four types of Portland cements were prepared. All of the 28 cement mortar mixes and their cement labels used in the study are shown in table-6.

The ordinary Portland cement and Portland slag cement are denoted by the symbol of PC and S, respectively, followed by their finenesses such as PC/3000: ordinary Portland cement with a Blaine fineness value of 3000 cm^2/g.

Slag Activity Index Determination: Since ground granulated blast furnace slag was ground to four different Blaine fineness values, namely, 3000 cm^2/g, 3500 cm^2/g, 4000 cm^2/g and 4500 cm^2/g, four different slag activity index test were conducted by using ASTM C 989[7] and ASTM C 109[26].

For the determination of the slag activity index, two kinds of mortar mixes having the same workability (a flow of 110±5%) were prepared. The first one is the reference cement mortar, containing 500 g Portland cement and 1375 g standard sand, and the second one is slag-reference cement mortar, containing 250 g Portland cement, 250 g ground granulated blast furnace slag and 1375 g standard sand. Using ASTM C 109 [26], 5 cm cube specimens were cast with each of the mortars and their 7-and 28-day compressive strengths were determined using the formula:

Slag Activity Index, % = (SP/P) ×100 (2)

Where SP the average compressive strength of slag-reference mortar cubes is at designated ages in MPa and P is the average compressive strength of reference cement mortar cubes at designated ages, in MPa[25].

Cement Mixes: For the purpose of investigating the effect of grinding technique on the Portland slag cements, 24 different mixes were prepared using one type of Portland cement clinker having four different Blaine fineness values (3000 cm^2/g, 3500 cm^2/g, 4000 cm^2/g and 4500 cm^2/g) and one type of granulated blast furnace slag having four different Blaine fineness values (3000 cm^2/g, 3500 cm^2/g, 4000 cm^2/g and 4500 cm^2/g) with one replacement amount (10%,20%,30% slag by weight). In addition to these, 4 different Portland cement control mixes were prepared using one type of Portland cement clinker having four different Blaine fineness values (3000 cm^2/g, 3500 cm^2/g, 4000 cm^2/g and 4500 cm^2/g) in order to compare with the Portland slag cements produced by separate grinding and together grinding techniques. All the tested mortars including the control cement were designed to have the same workability, meaning that water/ (cement+slag) ratio and water/ cement ratio were kept constant in accordance with TS EN 196-1 [22] in order to compare the 2-, 7-, 28-and 90-day flexural and compressive strength values.

Preparation of the Specimens: The mortar specimens were prepared using laboratory mixer and then fresh mortars were placed into the rectangular mold prisms having dimensions of 40×40×160 mm for compressive and flexural strength development tests in accordance with TS EN 196-1[22].

Curing of the Specimens: Specimens were placed into the moulds for 24 hours and then they were immersed in water at 20±1 °C temperature in the curing room having a humidity and the temperature around 90% and 20°C, respectively. The specimens were taken out of water 30 minutes before testing for flexural and compressive strength development.

Tests Performed on Portland Slag Cement Mortars and Pastes: Flexural and Compressive Strength Tests: For flexural strength tests, three specimens from each mix were prepared and tested. In flexural strength test, each specimen was supported from the two points each 2cm from the ends of the 16 cm length beam and the center-point loading was applied. The load was applied at the rate of 5±1 kgf/sec. The maximum load indicated by the testing machine, namely; Losenhausen having a capacity of 1 ton, was recorded and the tensile strength was calculated using the relation

$$\sigma = 1.5PL/b^3 \qquad (3)$$

Where P is the average of the applied load for the specimen, in kilogram-force, L is the span length, in centimeters; b is the height of the specimen, in centimeters[25].

Table-6
Cement Labels used in the Study the cement types

Mineral Label		**Portland Cement Clinker Gypsum**		**Slag**		**Cement**
Blaine Fineness(cm^2/g)	**% by Weight**	**Blaine Fineness(cm^2/g)**	**% by Weight**	**Blaine Fineness(cm^2/g)**	**% by Weight**	
6300	4	3000	100	-	-	PC-3000
6300	4	3500	100	-	-	PC-3500
6300	4	4000	100	-	-	PC-4000
6300	4	4500	100	-	-	PC-4500
6300	4	3000	90	3000	10	S S10/3000
6300	4	3000	80	3000	20	S S20/3000
6300	4	3000	70	3000	30	S S30/3000
6300	4	3500	90	3500	10	S S10/3500
6300	4	3500	80	3500	20	S S20/3500
6300	4	3500	70	3500	30	S S30/3500
6300	4	4000	90	4000	10	S S10/4000
6300	4	4000	80	4000	20	S S20/4000
6300	4	4000	70	4000	30	S S30/4000
6300	4	4500	90	4500	10	S S10/4500
6300	4	4500	80	4500	20	S S20/4500
6300	4	4500	70	4500	30	S S30/4500
6300	4	3000	90	3000	10	T S10/3000
6300	4	3000	80	3000	20	T S20/3000
6300	4	3000	70	3000	30	T S30/3000
6300	4	3500	90	3500	10	T S10/3500
6300	4	3500	80	3500	20	T S20/3500
6300	4	3500	70	3500	30	T S30/3500
6300	4	4000	90	4000	10	T S10/4000
6300	4	4000	80	4000	20	T S20/4000
6300	4	4000	70	4000	30	T S30/4000
6300	4	4500	90	4500	10	T S10/4500
6300	4	4500	80	4500	20	T S20/4500
6300	4	4500	70	4500	30	T S30/4500

Table-7
The Description of the Abbreviations Used for the Cement Types

Type of Grinding:
S-Separate grinding Together grinding
First number following the source indicated: Percent of slag by weight of Portland cement clinker
The last number following the dash sign: Blaine fineness of the cement in cm^2/g

Since the specimen broke approximately at the midpoint, two identical specimens were obtained to be tested for compressive strength determination. A 4×4 cm metal plate was used to apply the compressive load to the specimen providing 4×4 cm cross-sectional area for the specimen. The load was increased 10-20 kgf/cm^2 every second by using Utest type compressive strength testing machine having a capacity of 30 tons. The compressive strength was calculated using the relation

$$\sigma = P/A \quad (4)$$

Where P is the average load, in kilogram-force, and A is the cross-sectional area of the specimen, in square centimeters[25].

Normal Consistency and Setting Time: The normal consistency and setting time of cement pastes were determined using a Vicat apparatus according to the ASTM C 187[23] and ASTM C 191[24], respectively. For the normal consistency test, 650 g cement mixed with water in laboratory mixer and the prepared cement paste were molded in ball shape and tossed six times through a free path from one hand to another. Then, cement paste was pressed into the ring completely and located under the plunger of Vicat apparatus. Finally, the settlement of the plunger in the paste after 30 seconds was recorded in units of millimeters, which should be in the range of 10±1mm, in accordance with the ASTM C 187[23].

For the setting time test, the cement paste preparation was the same as the normal consistency test procedure. Then, the cement paste was located under the needle of Vicat apparatus, and by gently releasing the weighted needle onto the surface of the paste, penetration in mm was recorded after 30 seconds. For initial setting the settlement of the needle should be in 25 mm penetration and for final setting it should be in 0-1 mm penetration.

Results and Discussion

Slag Activity Indices: The 7-day and 28-day compressive strength values for 5 cm cubic mortar specimens were determined according to the ASTM C 989[7] and the slag activity indices were calculated by using Eqn. 10 and were tabulated in table 8.

The results indicated that the grade of the mortar mixes having different Blaine fineness values had the same grade 100. However, increasing the Blaine fineness values of the mortar mixes improved both the 7-day and 28-day slag activity indices. This means that in order to increase the quality of the slag, in other words, to increase the grade of the slag, the granulated blast furnace slag particles should be ground much finer.

Flexural Strength of Cements: The flexural strength of the Portland slag cements produced by separate grinding and Together grinding and the control Portland cements were determined by using equation 4 for 2, 7, 28, and 90 days and are given in table 9.

As seen in that table, the Together grinding Portland slag cements show higher strength values than the separately ground ones for the Blaine fineness values of 3000 cm^2/g and 3500 cm^2/g at 2 and 7 days. However, for Blaine fineness values of 4000 cm^2/g and 4500 cm^2/g, the separately ground Portland slag cements have higher strength values than the Together grinding ones at 2 and 7 days. For 28 days, the flexural strength of the Together grinding Portland slag cements show more or less the same values with the separately ground ones for all of the Blaine fineness values. Finally, the flexural strength of the separately ground Portland slag cements show higher values than the Together grinding ones again for all of the Blaine fineness values at 90 days.

Table-8
7-and 28-Day Compressive Strengths of Specimens and Their Slag Activity Indices

Mortar Mix	7-Day Compressive Strength (MPa)	7-Day Slag Activity Index (%)	28-Day Compressive Strength (MPa)	28-Day Slag Activity Index (%)
PC (3500)	30.9	—	42.8	—
S10-PC (3000)	22.8	74	41.6	97
S20-PC (3000)	23.2	75	41.8	98
S30-PC (3000)	23.4	76	42.3	99
S10-PC (3500)	24.6	80	42.9	100
S20-PC (3500)	25	81	43.4	101
S30-PC (3500)	25.4	82	43.7	102
S10-PC (4000)	27.2	88	45.1	105
S20-PC (4000)	27.7	90	45.7	107
S30-PC (4000)	28.1	91	46.1	108
S10-PC (4500)	29	94	47.9	112
S20-PC (4500)	29.6	96	48.2	113
S30-PC (4500)	30.1	97	48.6	114

Table-9
Flexural Strength Values of Portland cement Control and Portland Slag Cement Specimens

Flexural Strength (MPa)				Cement
2 Days	**7 Days**	**28 Days**	**90 Days**	
6.1	7.8	8.3	9.3	**PC-3000**
6.3	7.9	8.5	9.5	**PC-3500**
7.5	8.4	9.2	9.8	**PC-4000**
7.5	8.7	9.6	10.9	**PC-4500**
4.1	5.4	7.8	7.9	**S S10/3000**
4.2	5.5	7.8	8.1	**S S20/3000**
4.1	5.5	8.1	8.3	**S S30/3000**
4.9	6.9	8.5	8.9	**S S10/3500**
4.9	7	8.6	9	**S S20/3500**
5.0	7	8.5	9.1	**S S30/3500**
5.1	7	8.5	9.2	**S S10/4000**
5.1	7.1	7.6	9.2	**S S20/4000**
5.2	7.1	8.7	9.4	**S S30/4000**
5.4	7.2	8.8	9.5	**S S10/4500**
5.3	7	8.7	9.5	**S S20/4500**
5.4	7.3	8.9	9.6	**S S30/4500**
4.5	6.1	8.1	8.2	**T S10/3000**
4.5	6.1	8	8.3	**T S20/3000**
4.6	6.3	8.3	8.4	**T S30/3000**
4.5	6.1	8.2	8.4	**T S10/3500**
4.6	6.2	8.3	8.4	**T S20/3500**
4.6	6.3	8.4	8.5	**T S30/3500**
4.7	6.4	8.4	8.6	**T S10/4000**
4.8	6.5	8.6	8.7	**T S20/4000**
4.8	6.6	8.7	8.8	**T S30/4000**
4.9	6.6	8.6	8.8	**T S10/4500**
4.9	6.7	8.7	8.9	**T S20/4500**
5	6.9	8.8	9	**T S30/4500**

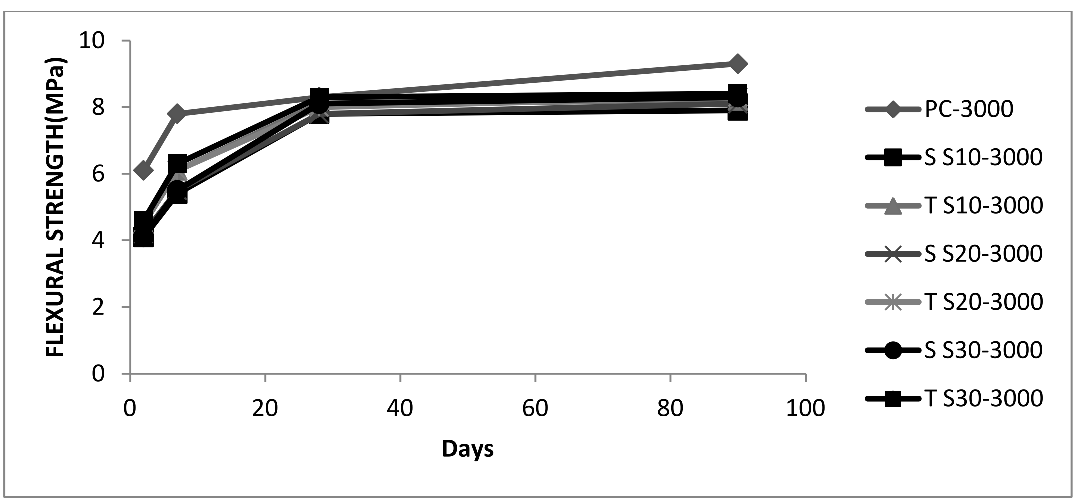

Figure-1
Comparison Flexural Strength Values of Portland cement Control and Portland Slag Cement Specimens (separately grinding Portland slag cements and together ground ones) for the Blaine fineness values of 3000 cm^2/g

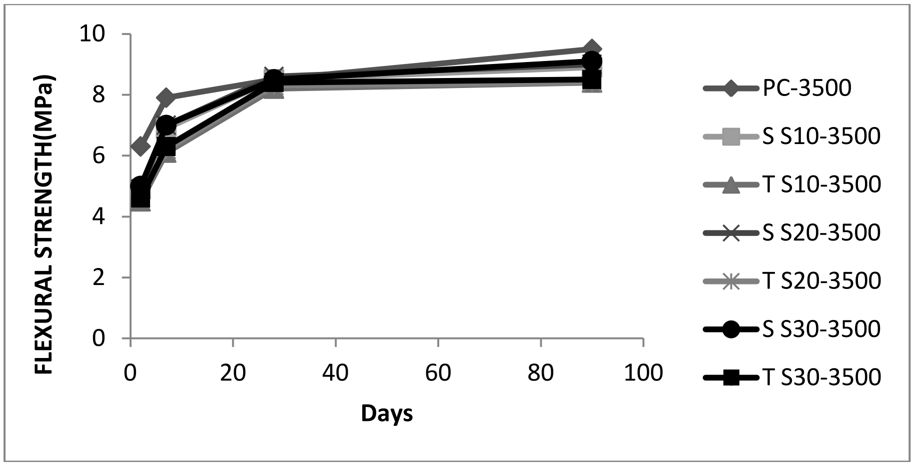

Figure-2
Comparison Flexural Strength Values of Portland cement Control and Portland Slag Cement Specimens (separately grinding Portland slag cements and together ground ones) for the Blaine fineness values of 3500 cm^2/g

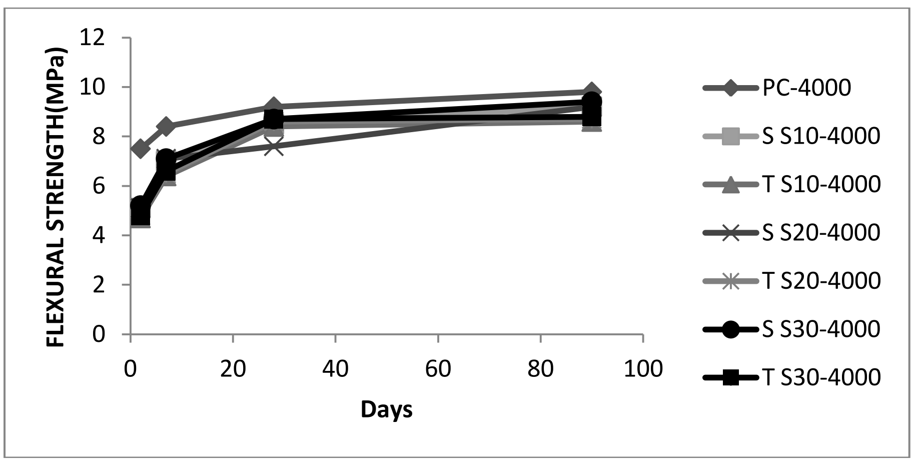

Figure-3
Comparison Flexural Strength Values of Portland cement Control and Portland Slag Cement Specimens (separately grinding Portland slag cements and together ground ones) for the Blaine fineness values of 4000 cm^2/g

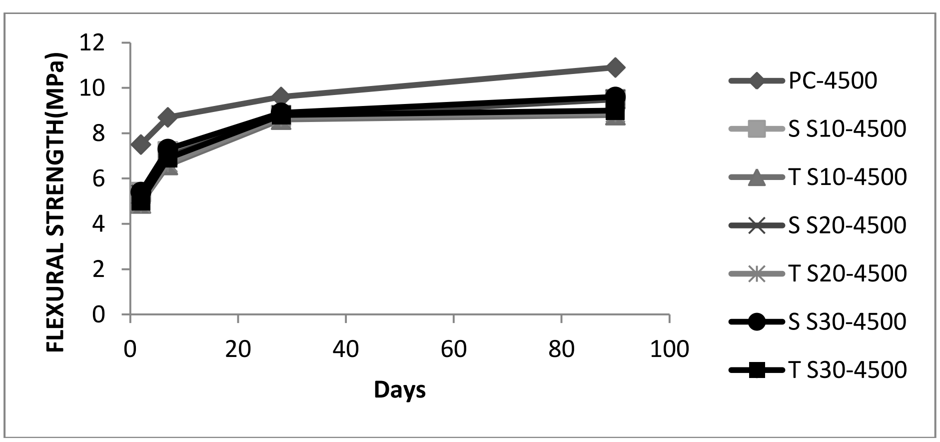

Figure-4
Comparison Flexural Strength Values of Portland cement Control and Portland Slag Cement Specimens (separately grinding Portland slag cements and together ground ones) for the Blaine fineness values of 4500 cm^2/g

Compressive Strength of Cements: The compressive strength values of the Portland slag cements produced by the separate grinding and Together grinding methods and the control Portland cements were determined by using equation 4 for 2, 7, 28, and 90 days as presented in table 10.

The compressive strength development with respect to Portland cement control specimens for 2, 7, 28 and 90 days of Portland slag cements produced by separate grinding and together grinding are plotted in figures 5 through 8, respectively.

From figure 5 through 8, it is seen that the 2-, 7-, 28-and 90-day compressive strength of the Together grinding Portland slag cements have higher values than the separately ground Portland slag cements for the Blaine fineness values of 3000 cm^2/g, 3500 cm^2/g and 4000 cm^2/g. On the other hand, for the Blaine fineness values of 4500 cm^2/g, separately ground Portland slag cement specimens have a little bit higher 2-, 7-, 28-, and 90-day compressive strength values than the Together grinding ones.

The compressive strength development of the separately ground and Together grinding Portland slag cements with respect to Portland cement control specimens are plotted according to the Blaine fineness values, namely, 3000 cm^2/g, 3500 cm^2/g, 4000 cm^2/g and 4500 cm^2/g in figures 5 through 8, respectively.

Table-10
Compressive Strength Values of Portland cement Control and Portland Slag Cement Specimens

Compressive Strength (MPa)				**Cement**
2 Days	**7 Days**	**28 Days**	**90 Days**	
25.3	40.4	53.0	57.2	**PC-3000**
28.8	42.4	60.1	63.9	**PC-3500**
34	44.7	61.2	64.8	**PC-4000**
36	47.1	65.7	68.3	**PC-4500**
16.3	25	45.8	54.7	**S S10/3000**
16.6	25.5	46	55.2	**S S20/3000**
17.1	25.9	46.4	55.7	**S S30/3000**
20.6	29.7	50.2	61.1	**S S10/3500**
20.6	30	50.5	61.5	**S S20/3500**
20.9	30.3	51.1	62	**S S30/3500**
22.3	33.1	55.3	66.9	**S S10/4000**
22.6	33.4	55.8	56.8	**S S20/4000**
22.9	33.7	56.1	67.8	**S S30/4000**
23.8	36.1	60.3	71	**S S10/4500**
24	36.9	60.7	71.7	**S S20/4500**
24.2	41.3	60.9	72.2	**S S30/4500**
18.9	28.1	47.6	60	**T S10/3000**
19.2	28.5	48	60.4	**T S20/3000**
19.2	28.4	48.1	60.8	**T S30/3000**
21.8	31.1	52.9	67.7	**T S10/3500**
22.1	31.8	53.6	68.4	**T S20/3500**
22.6	32.6	54.5	69	**T S30/3500**
21.8	33.8	55.5	69	**T S10/4000**
22.3	34.2	56.3	69.6	**T S20/4000**
22.7	34.5	56.9	67.2	**T S30/4000**
24.0	35.3	56.9	70.1	**T S10/4500**
24.7	36	57.4	70.6	**T S20/4500**
24.9	36.1	58.1	71.3	**T S30/4500**

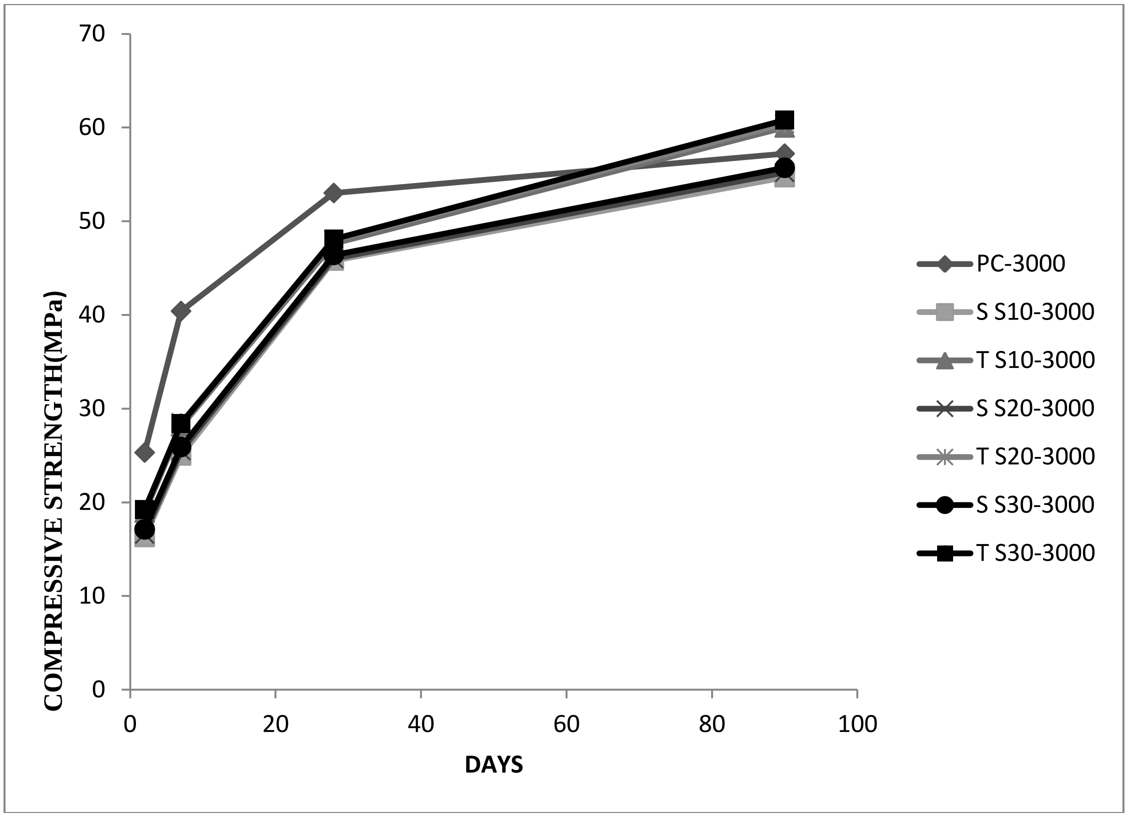

Figure-5
Compressive Strength with Respect to Control for 3000 cm^2/g Blaine Fineness

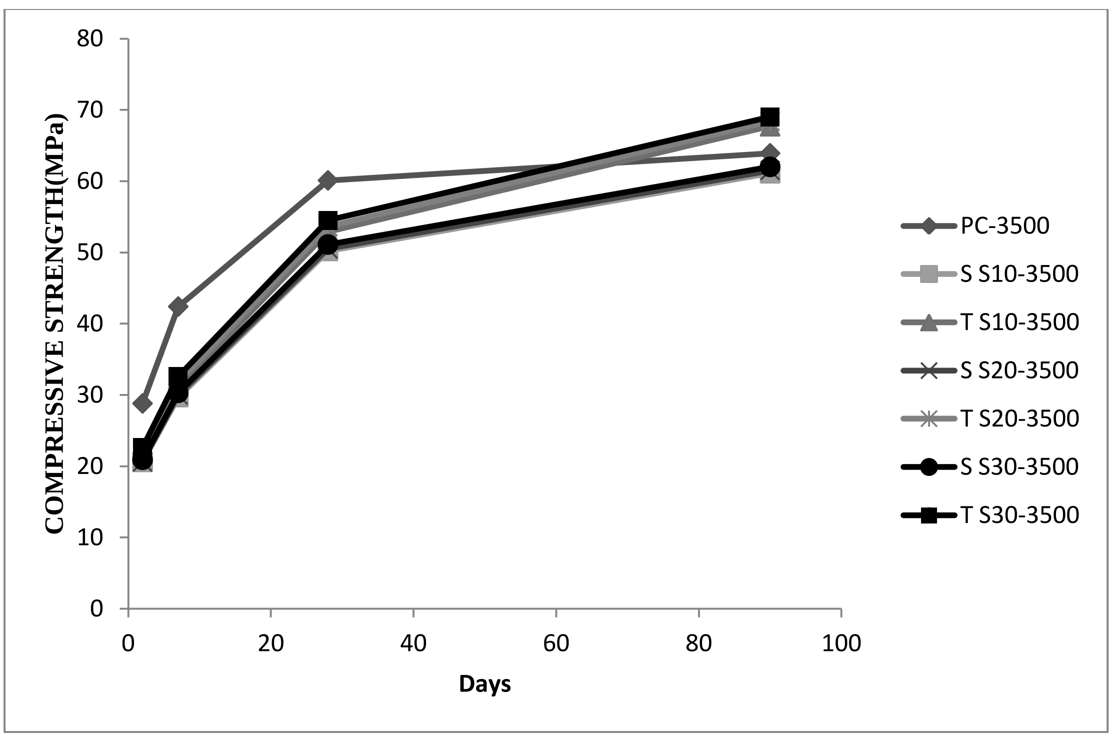

Figure-6
Compressive Strength with Respect to Control for 3500 cm^2/g Blaine Fineness

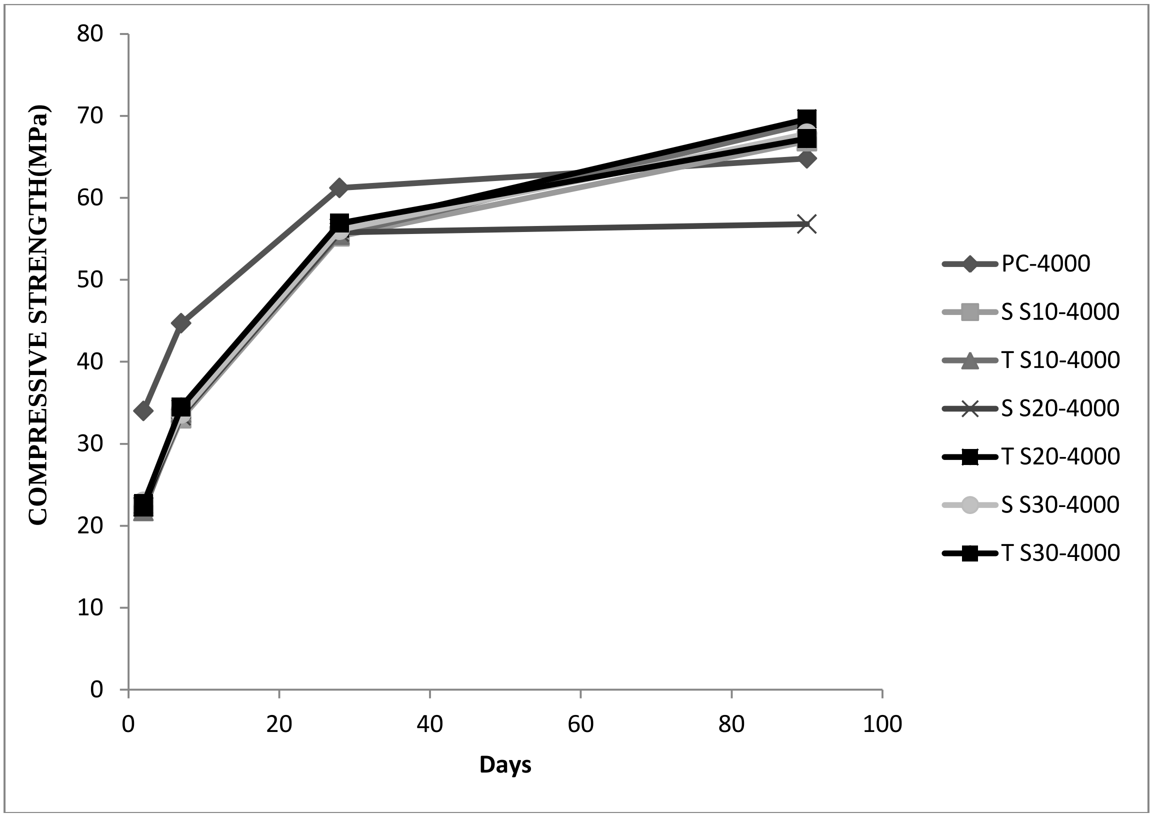

Figure-7
Compressive Strength with Respect to Control for 4000cm^2/g Blaine Fineness

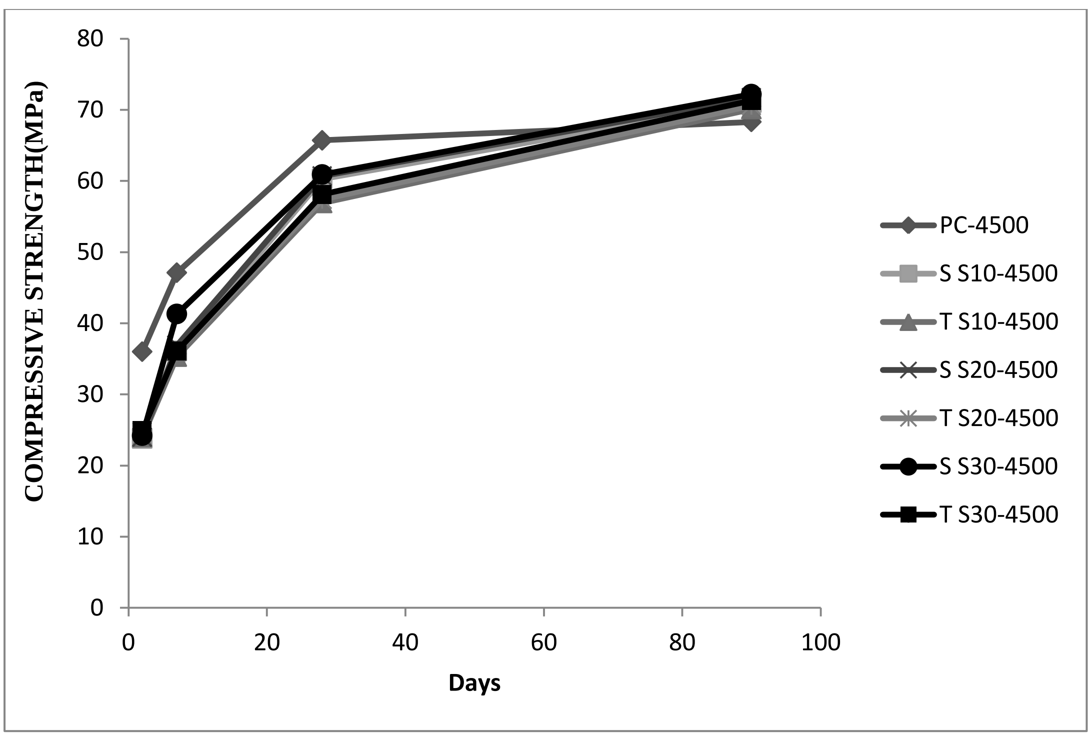

Figure-8
Compressive Strength with Respect to Control for 4500 cm^2/g Blaine Fineness

In figure-5 through 8, it is seen that at early ages of testing (2 and 7 days) of compressive strength of the Portland slag cement specimens are much lower than the Portland cement control specimens. However, after 7 days, the compressive strength values of the Portland slag cements starts to increase and reaches about the 90% of the Portland cement control specimen values. For 90 days of testing, for Together grinding Portland slag cements have higher compressive strength values than the Portland cement control specimens for all the Blaine fineness values. On the other hand, for separately ground Portland slag cement specimens, they have only passed the Portland cement control specimens for the Blaine fineness values of 4000 cm^2/g and 4500 cm^2/g.

Conclusion

As a result of the experimental study, the following conclusions could be made: The grinding time required for slag particles are higher than Portland cement clinker particles for all the tested Blaine fineness values; therefore, the grind ability of the slag is observed to be lower than the grind ability of the clinker.

According to the Rosin-Rammler-Bennett particle size distribution graphs, Portland cement clinker particles show wider size distribution than the slag particles. Moreover, the particle size distributions of the Together grinding Portland cement clinker and slag particles are in between the particle size distributions of the slag and Portland cement clinker particles. However; it is not their weighted average values, it is closer to the slag particles.

Portland slag cements, whether separately ground or Together grinding, require slightly more water than the Portland cements for normal consistency circumstances for all of the tested Blaine fineness values. The reason of this may be the specific gravity of the slag particles (2.84) which is smaller than that of the Portland cement particles.

The initial and final setting times of each cement paste satisfies the limits according to ASTM C 1157 which are 45 minutes and 420 minutes, respectively. Moreover, the initial and the final setting times of all the Portland slag cement pastes are higher than the Portland cement pastes for all the tested Blaine fineness values.

The initial and the final setting times of separately ground Portland slag cement pastes are shorter than those of the Together grinding Portland slag cement pastes. Furthermore, as the Blaine fineness values increase, the initial and final setting times shorten because the rate of hydration of the cement paste increases when the Blaine fineness values increase. Finally, for all of the cement pastes, the initial and final setting times are inversely proportional to their water demand for normal consistency. The 2-, 7-, 28-and 90-day compressive strength values of the Together grinding Portland slag cements are higher than the compressive strength values of the separately ground ones for the Blaine fineness values of 3000 cm^2/g, 3500 cm^2/g and 4000 cm^2/g. However, for the Blaine fineness value of 4500 cm^2/g, the compressive strength values of the separately ground Portland slag cements are a little bit higher than the Together grinding ones.

The compressive strength development of Portland cement control specimens have higher values than those of the Portland slag cement specimens for 2,7 and 28 days. For 90-day testing, Together grinding Portland slag cements have higher compressive strength values than the Portland cement control specimens for all the Blaine fineness values. On the other hand, for separately ground Portland slag cement specimens, they have only passed the Portland cement control specimens for the Blaine fineness values of 4000 cm^2/g and 4500 cm^2/g.

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