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An experimental study on optimum usage of GGBS for the compressive strength of concrete

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Abstract

This paper presents a laboratory investigation on optimum level of ground granulated blast-furnace slag (GGBS) on the compressive strength of concrete. GGBS was added according to the partial replacement method in all mixtures. A total of 32 mixtures were prepared in four groups according to their binder content. Eight mixes were prepared as control mixtures with 175, 210, 245 and 280 kg/m^3 cement content in order to calculate the Bolomey and Féret coefficients (K_B, K_F). For each group 175, 210, 245 and 280 kg/m^3 dosages were determined as initial dosages, which were obtained by removing 30 percent of the cement content of control concretes with 250, 300, 350, and 400 kg/m^3 dosages. Test concretes were obtained by adding GGBS to concretes in an amount equivalent to approximately 0%, 15%, 30%, 50%, 70%, 90% and 110% of cement contents of control concretes with 250, 300, 350 and 400 kg/m^3 dosages. All specimens were moist cured for 7, 14, 28, 63, 119, 180 and 365 days before compressive strength testing.

The test results proved that the compressive strength of concrete mixtures containing GGBS increases as the amount of GGBS increase. After an optimum point, at around 55% of the total binder content, the addition of GGBS does not improve the compressive strength. This can be explained by the presence of unreacted GGBS, acting as a filler material in the paste.

Keywords: Calcium–silicate–hydrate (C–S–H); Compressive strength; Efficiency; GGBS; Strength development

1. Introduction

Mineral admixtures such as ground granulated blast-furnace slag (GGBS), fly ash and silica fume are commonly used in concrete because they improve durability and reduce porosity; improve the interface with the aggregate. Economics (lower cement requirement), energy, and environmental considerations have had a role in the mineral admixture usage as well as better engineering and performance properties. The lower cement requirement also leads to a reduction for CO_2 generated by the production of cement [1–4]. The engineering benefits from the use of mineral admixtures in concrete result partly from their particle size distribution characteristics, and partly from the pozzolanic and cementitious reactivity [5,6].

Granulated blast-furnace slag is a by-product in the manufacture of pig iron and the amounts of iron and slag obtained are of the same order. The slag is a mixture of lime, silica, and alumina, the same oxides that make up Portland cement, but not in the same proportion [7,8]. The composition of blast-furnace slag is determined by that of the ores, fluxing stone and impurities in the coke charged into the blast furnace. Typically, silicon, calcium, aluminum, magnesium, and oxygen constitute 95% or more of the blast-furnace slag. To maximize hydraulic (cementitious) properties, the molten slag must be chilled rapidly as it leaves the blast furnace. Rapid quenching or chilling minimizes crystallization and converts the molten slag into fine-aggregate-sized particles generally smaller than a 4.75 mm (No. 4) sieve, composed predominantly of glass.

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This product is referred to as granulated iron blast-furnace slag. GGBS is obtained by finely grinding of this material [9].

The hydration of the Portland cement results from the production of portlandite crystal [$Ca(OH)_2$] and amorphous calcium silicate hydrate gel [$C_3S_2H_3$] (C–S–H) in large amounts. Hydrated cement paste involves approximately 70% C–S–H, 20% $Ca(OH)_2$; 7% sulpho-aluminates and 3% secondary phases. The $Ca(OH)_2$ which appears as the result of the chemical reactions affect the quality of the concrete adversely by forming cavities as it is partly soluble in water and lacks enough strength. The use of ground granulated blast-furnace slag has a positive effect on binding the $Ca(OH)_2$ compound, which decreases the quality of the concrete. At the end of the reaction of the slag and $Ca(OH)_2$, hydration products, such as C–S–H gel, are formed [10–12].

The cementitious and pozzolanic behavior of ground granulated blast furnace slag is essentially similar to that of high-calcium fly ash. At 40%, 50% or 65% cement replacement by weight, Hogan and Meusel [13] found that up to 3 days of age, strength contribution of slag to ASTM C 109 [14] mortars was low; however, strength similar to the reference Portland cement was achieved at 7 days, and higher strength thereafter [5].

ASTM C 989 defines slag activity index (SAI) as the percentage ratio of the average compressive strength of slag cement (50–50%) mortar cubes to the average compressive strength of reference cement mortar cubes at a designated age. According to ASTM C 989, GGBS is classified into three grades – Grade 80, Grade 100, and Grade 120, depending on the relative compressive strength [9,15,16].

Hwang and Lin [17] have determined compressive strength of GGBS mortars at different ages and at various replacement levels. They showed that there is a maximum percentage of GGBS replacement to obtain an equivalent strength of the concrete mixture without GGBS. Papadakis [10,18] studied the efficiency factor and design of supplementary cementitious materials (SCM) in concrete and reported that when SCM replaced aggregates, higher strength values, compared to the control mixtures were obtained. When SCM replaces cement, the strength was reduced. In order to estimate the k values, the following empirical Eq. (1) was used. Using the mean measured values of the compressive strength of the control specimen, the parameter K was estimated. The efficiency factor (k) values for the SCM-concrete of the present work were calculated using Eq. (2).

$$f_c = K\left(\frac{1}{W/C} - a\right) \tag{1}$$

$$f_c = K\left(\frac{1}{W/(C+kP)} - a\right) \tag{2}$$

Babu and Rao [18] investigated the efficiency factor of GGBS in concrete. It is reported that the overall strength efficiency factor (k) of GGBS was a combination of the two factors – the general efficiency factor (k_e) and the percentage efficiency factor (k_p) which depend on the age and percentage of replacement, respectively. Pekmezci and Akyuz [19] have calculated the maximum content of the natural pozzolan for maximizing the compressive strength of concrete, and found the optimum pozzolan-to-cement ratio as 0.28. In this work, Bolomey strength relationship was used. The Bolomey and (a) coefficients were calculated by using concrete mixtures with no natural pozzolan. By using the compressive strength values of the concretes with natural pozzolan, and the Bolomey and (a) coefficients calculated from the control mixes, the cement content to replace the natural pozzolan was calculated. Oner et al. [11], have used Bolomey and Féret equations, and calculated the optimum fly ash content to maximize the strength as 40%.

In this paper, an experimental investigation of optimum usage of GGBS in concrete was carried out. The optimum values and efficiency of GGBS were determined for concrete with various cement dosages by the compressive strength test results, Bolomey and Féret strength equations.

2. Experimental programme

2.1. Materials

2.1.1. Cement

The cement used was CEM I 42.5 ordinary Portland cement which conformed to EN 197-1 [20]. Specific gravity of cement used was 3.10. The Blaine specific surface area was 3513 cm^2/g. Initial and final setting times of the cement were 02:42 and 03:32 h, respectively. The remaining cement on 200, 90, and 45 μm sieves were 0%, 7.5% and 24.2%, respectively. The chemical composition and physical properties are given in Tables 1 and 2.

Table 1
Chemical compositions (%) of binding materials

Binder	Chemical compositions (%)									LOI[a]	IM[b]
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl^-		
Cement	20.72	4.88	2.95	61.83	1.39	2.33	0.19	0.67	0.0060	3.17	0.63
GGBS	39.18	10.18	2.02	32.82	8.52	–	1.14	0.30	–	1.0	0.88

[a] Loss on ignition.
[b] Insoluble material.

Table 2
Physical properties of binding materials

Physical test	Cement	GGBS
Specific gravity (g/cm^3)	3.10	2.87
Fineness: specific surface (cm^2/g)	3513	4250
Fineness (retained on 90 μm sieve)	7.5	0
Fineness (retained on 45 μm sieve)	24.2	0.8
Vicat time of setting (min)		
Initial	162	–
Final	212	–

2.1.2. Ground granulated blast-furnace slag (GGBS)

A Grade 100 class (ASTM C 989) [15] GGBS was provided by a cement manufacturer in Turkey. The slag activity index of GGBS was 75.2% and 96.3% for 7 and 28 days, respectively. The specific gravity was 2.87 gr/cm^3 and Blaine specific surface area was 4250 cm^2/g. The GGBS remaining on 90 μm and 45 μm sieves were 0% and 0.8%, respectively. The chemical composition and physical properties of GGBS are presented in Tables 1 and 2.

2.1.3. Aggregates

Crushed limestone with a density of 2.70 gr/cm^3, a maximum particle size of 19 mm and a fineness modulus of 5.61 was used as coarse aggregate in this study. The fine aggregate was crushed limestone powder with a density of 2.68 gr/cm^3, and fineness modulus of 2.25. Volume percentages of coarse and fine aggregate were 50% and 50%, respectively and kept the same in all mixtures. Specific gravity, fineness modulus and grading of fine, coarse and mix aggregates are given in Table 3.

2.2. Specimen preparation and curing

A total of 32 mixtures were prepared. Eight of them were prepared as control mixtures, four of which were mix designs with 250, 300, 350 and 400 kg/m^3 cement content and the remaining were four mix designs with 175, 210, 245 and 280 kg/m^3 cement content, four groups of mixtures were prepared, each containing eight recipes and using the cement content of one of the control mixture as the base for the recipe (Table 4).

All the concrete mixtures were mixed for a total of 4 min. in a laboratory pan mixer. From each concrete mixture, forty-two 150 mm cubic were cast for the determination of the compressive strength. Casting of cubes was conducted in two layers. Each layer was compacted by internal vibration and top surface was leveled and smoothed using a trowel. After casting, all the molded specimens were covered with plastic sheets and water-saturated burlap and left in the curing room for 24 h at the temperature of 23 ± 2 °C. After 24 h, concrete specimens were demolded and cured in 20 ± 2 °C lime-saturated water until the time of the compressive strength. The test specimens were cured according to ASTM C192-88 [21].

2.3. Testing of the specimens

The mixtures of concrete containing GGBS added partial cement replacement of 0%, 15%, 30%, 50%, 70%, 90% and 110% by weight were tested for compressive strength development. The workability of fresh concrete including slump was measured and air content and unit weight of the fresh concrete were determined after the mixing was finished. The slump of the control mixtures was 120 mm and the water was adjusted to have a concrete with a slump of 120 ± 10 mm for the GGBS concrete. The slump and air content of fresh concrete were determined following ASTM C143 [22] and ASTM C231-04 [23], respectively.

The compressive strength of hardened concrete was measured. For each mixture, the compressive strength was determined on six cubic specimens of 15 cm at 7, 14, 28, 63, 119, 180 and 365 days. At the age of 7, 14, 28, 63, 119, 180 and 365 days, the specimens were taken out of water and tested for strength of a temperature of 23 ± 2 °C. Concrete specimens were coded with cement content and GGBS content of 1 m^3. The compositions of the concretes are given in Table 4.

3. Results and discussion

3.1. Properties of fresh concrete

The unit weight, slump, and air content of the fresh concrete are given in Table 4. The effect of GGBS on the workability of concrete can be seen in this table. The water content in this table was determined according to target workability (120 ± 10 mm slump). As the GGBS content increased, the water used in the mix design also increased. Since GGBS replaced the aggregate portion of the control

Table 3
Physical properties and sieve analysis of aggregates

Aggregate type	Specific gravity (g/cm^3)	Mix proportion (%)	Maximum size (mm)	Percentage passing Sieve size (mm)								Fineness modulus
				31.5	16	8	4	2	1	0.5	0.25	
Crushed limestone No II	2.70	20	19	100	77	1	0	0	0	0	0	6.22
Crushed limestone No I	2.70	30	12	100	100	62	8	4	3	1	1	5.21
Crushed limestone powder	2.68	50	4	100	100	100	100	76	49	30	20	2.25
Mix	2.69	100	19	100	95	69	52	39	25	15	10	3.95

Table 4
Mix proportioning (kg/m^3) and properties of fresh concrete

Concrete	Mix proportioning (kg/m^3)					Properties of fresh concrete				
	Cement	GGBS	Water	CA[a]	FA[b]	Expected slump (mm)	Slump (mm)	Theoretical unit weight (kg/m^3)	Actual unit weight (kg/m^3)	Air content (%)
C250GGBS00.0	250	0	219	1111	732	120 ± 10	120	2312	2317	1.6
C175GGBS00.0	175	0	209	1166	768	120 ± 10	115	2318	2329	1.4
C175GGBS37.5	175	37.5	215	1135	748	120 ± 10	120	2310.5	2319	1.5
C175GGBS75.0	175	75	218	1109	731	120 ± 10	115	2308	2314	1.6
C175GGBS125.0	175	125	223	1073	707	120 ± 10	120	2303	2303	1.8
C175GGBS175.0	175	175	230	1033	681	120 ± 10	120	2294	2295	1.8
C175GGBS225.0	175	225	238	991	654	120 ± 10	120	2283	2286	1.7
C175GGBS275.0	175	275	248	948	624	120 ± 10	125	2270	2274	1.6
C300GGBS00	300	0	225	1075	708	120 ± 10	120	2308	2313	1.6
C210GGBS00.0	210	0	214	1140	751	120 ± 10	120	2315	2323	1.5
C210GGBS45.0	210	45	219	1106	729	120 ± 10	115	2309	2317	1.5
C210GGBS90.0	210	90	224	1072	707	120 ± 10	115	2303	2306	1.7
C210GGBS150.0	210	150	231	1027	677	120 ± 10	120	2295	2296	1.8
C210GGBS210.0	210	210	240	979	645	120 ± 10	120	2284	2284	1.8
C210GGBS270.0	210	270	251	927	611	120 ± 10	120	2269	2271	1.7
C210GGBS330.0	210	330	261	877	578	120 ± 10	125	2256	2260	1.6
C350GGBS00	350	0	232	1037	684	120 ± 10	120	2303	2306	1.7
C245GGBS00.0	245	0	218	1114	735	120 ± 10	120	2312	2323	1.4
C245GGBS52.5	245	52.5	225	1073	708	120 ± 10	115	2303.5	2307	1.7
C245GGBS105.0	245	105	230	1036	683	120 ± 10	120	2299	2302	1.7
C245GGBS175.0	245	175	239	982	647	120 ± 10	115	2288	2288	1.8
C245GGBS245.0	245	245	250	924	609	120 ± 10	125	2273	2271	1.9
C245GGBS315.0	245	315	263	864	569	120 ± 10	125	2256	2253	1.9
C245GGBS385.0	245	385	279	799	526	120 ± 10	125	2234	2233	1.8
C400GGBS00	400	0	239	999	659	120 ± 10	120	2297	2300	1.7
C280GGBS00.0	280	0	224	1087	716	120 ± 10	120	2307	2315	1.5
C280GGBS60.0	280	60	231	1041	686	120 ± 10	115	2298	2302	1.7
C280GGBS120	280	120	236	999	659	120 ± 10	115	2294	2295	1.8
C280GGBS200	280	200	247	936	617	120 ± 10	115	2280	2278	1.9
C280GGBS280	280	280	263	866	570	120 ± 10	120	2259	2254	2
C280GGBS360	280	360	278	796	525	120 ± 10	120	2239	2233	2
C280GGBS440	280	440	295	723	477	120 ± 10	125	2215	2213	1.8

[a] Coarse aggregate.
[b] Fine aggregate.

mixtures, the water content of the GGBS containing concretes increased due to higher specific surface of the GGBS particles. However, due to reactivity of the mineral pozzolan, the increase in the water content of the concrete mixtures containing GGBS does not necessarily present adverse results. Due to the pozzolanic properties of the mineral admixtures, the water-to-binder ratio of the concrete mixtures should be taken into account. As the water-to-binder ratio decreases with the addition of GGBS, the effect of GGBS on the workability can be considered as affirmative. In general, for a constant workability, the GGBS containing concrete mixtures require less water, compared to the concrete mixtures without any mineral admixtures [9,24]. The entrapped air content of the concrete ranged from 1.4% to 2%.

3.2. Compressive strength development

Compressive strength of concrete mixtures made with and without GGBS was determined at 7, 14, 28, 63, 119, 180 and 365 days of curing. The average of six samples was taken for every testing age. The compressive strength test results are given in Table 5.

It is observed that the early age strength values of GGBS concrete mixtures are lower than the control mixtures. As the curing period is extended, the strength values of the GGBS concrete mixtures increase more than the control mixtures. After 1 year, the GGBS concrete mixtures exhibit higher strength values compared to the control mixtures with equivalent binder content. Since the pozzolanic reaction is slow and depends on the calcium hydroxide availability, the strength gain takes longer time for the GGBS concrete. The chemical reaction of the Portland cement is expressed as follows:

$$\text{Cement}\,(C_3S,\,C_2S) + H_2O\,(H) \rightarrow \text{CSH–gel} + Ca(OH)_2\,(CH) \tag{3}$$

The pozzolanic reaction is [5,10,25];

$$Ca(OH)_2\ (CH) + SiO_2\ (S) + H_2O\ (H) \rightarrow \text{CSH–gel} \tag{4}$$

Table 5
Compressive strength gain of concretes

Concrete	Cube compressive strength (MPa)							Strength gain from 7 to 365 day (%)
	7 day	14 day	28 day	63 day	119 day	180 day	365 day	
C250GGBS00.0	15.3	17.6	22.7	23.2	23.7	24.6	25.9	69.3
C175GGBS00.0	9.2	9.7	13.0	13.3	13.6	14.1	14.5	57.6
C175GGBS37.5	12.7	13.4	18.1	19.3	20.0	20.5	21.4	68.5
C175GGBS75.0	16.4	17.4	23.5	26.8	28.1	29.0	30.5	86
C175GGBS125.0	18.6	20.2	27.0	31.7	34.8	36.2	38.4	106.5
C175GGBS175.0	19.1	20.6	27.8	33.1	36.5	38.2	40.8	113.6
C175GGBS225.0	18.5	20.1	27.2	32.9	36.1	38.0	40.9	121.1
C175GGBS275.0	17.1	18.5	25.1	30.4	33.7	35.8	38.7	126.3
C300GGBS00	19.9	22.7	28.9	29.8	30.4	31.5	33.1	66.3
C210GGBS00.0	12.4	13.7	17.5	18.0	18.3	18.8	19.8	59.7
C210GGBS45.0	16.7	18.3	23.6	25.0	26.7	27.6	28.9	73.1
C210GGBS90.0	21.2	23.1	30.0	33.0	35.8	37.1	39.1	84.4
C210GGBS150.0	23.9	26.1	34.0	40.0	43.4	45.2	47.9	100.4
C210GGBS210.0	24.4	26.6	34.9	40.9	45.4	47.4	50.5	107
C210GGBS270.0	24.1	26.3	34.5	40.7	45.3	47.5	50.7	110.4
C210GGBS330.0	22.2	24.3	31.8	37.8	42.4	44.7	47.9	115.8
C350GGBS00	24.9	27.8	35.0	35.9	36.5	37.9	40.0	60.6
C245GGBS00.0	16.1	17.9	22.6	23.0	23.5	24.3	25.6	59
C245GGBS52.5	20.8	22.9	29.0	30.3	33.0	34.3	36.2	74
C245GGBS105.0	25.6	28.3	36.1	39.2	42.5	44.3	46.9	83.2
C245GGBS175.0	29.6	32.4	41.4	47.7	51.7	54.0	57.4	93.9
C245GGBS245.0	30.1	33.0	42.3	48.5	53.5	56.0	59.7	98.3
C245GGBS315.0	29.5	32.4	41.5	48.1	53.7	56.3	60.2	104.1
C245GGBS385.0	26.6	29.2	37.5	43.5	49.0	51.7	55.2	107.5
C400GGBS00	29.1	32.6	40.4	41.5	42.4	44.0	46.3	59.1
C280GGBS00.0	19.6	21.9	27.5	28.3	28.9	29.8	31.2	59.2
C280GGBS60.0	24.0	26.7	33.7	35.2	37.8	39.1	41.1	71.3
C280GGBS120	29.8	33.1	41.8	45.9	49.1	51.0	53.8	80.5
C280GGBS200	33.8	37.5	47.5	54.5	58.3	60.8	64.5	90.8
C280GGBS280	34.4	38.1	48.4	55.3	59.9	62.6	66.7	93.9
C280GGBS360	33.3	37.0	47.0	54.9	59.9	62.8	67.2	101.8
C280GGBS440	30.2	33.5	42.7	49.6	55.2	58.3	62.4	106.6

As it can be seen from the above reactions, calcium hydroxide is produced by the hydration of Portland cement and consumed by the pozzolanic reaction. The pozzolanic reaction can only takes place after the Portland cement hydration starts [26]. It can be seen that the mixture with the highest GGBS addition presents the highest compressive strength increase from the seventh day to one year. This shows that as the GGBS content is increased, the strength gain increases in time. The compressive strength gains of the GGBS concrete mixtures are presented in Figs. 1–4.

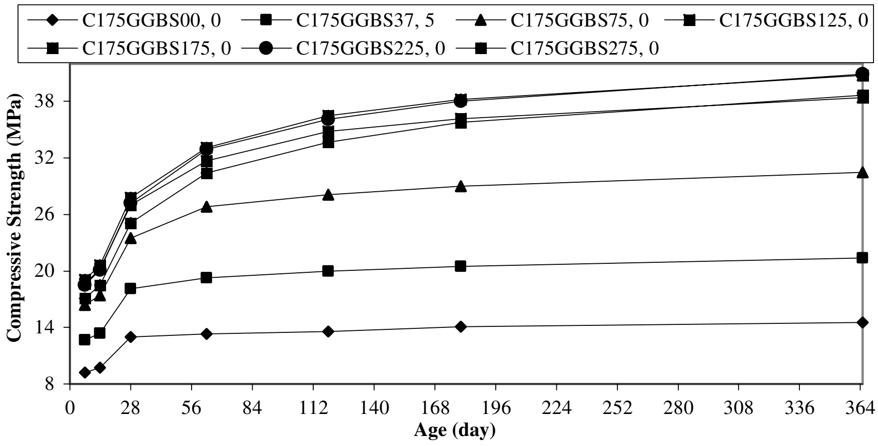

Fig. 1. Compressive strength development of 175 dosage concrete.

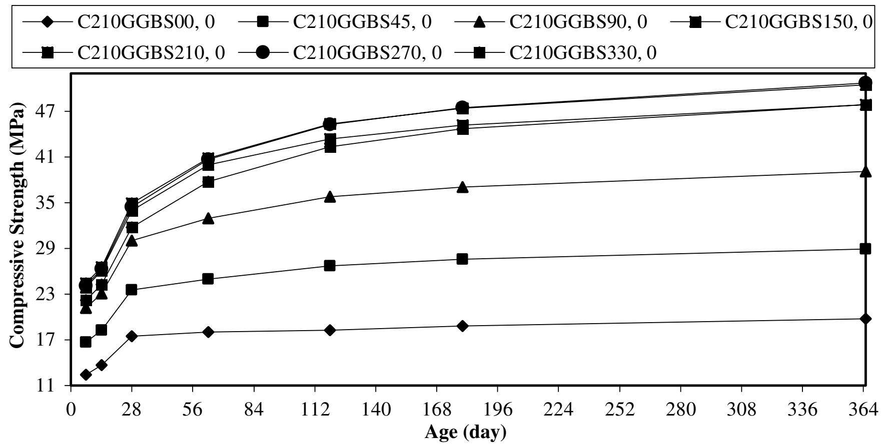

Fig. 2. Compressive strength development of 210 dosage concrete.

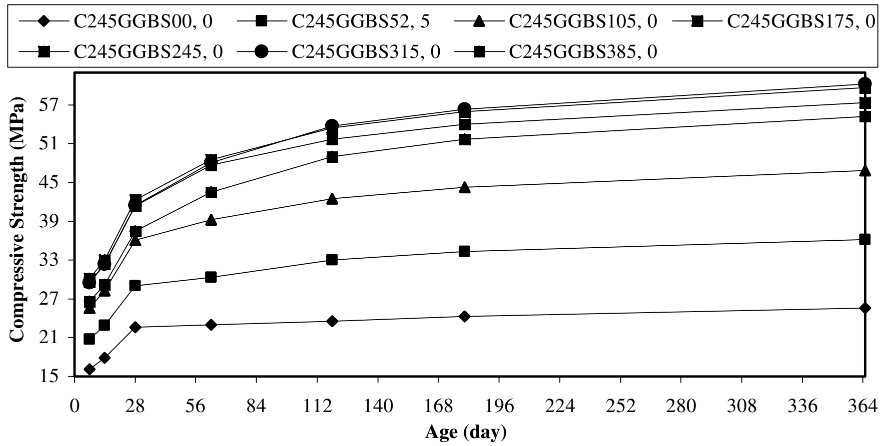

Fig. 3. Compressive strength development of 245 dosage concrete.

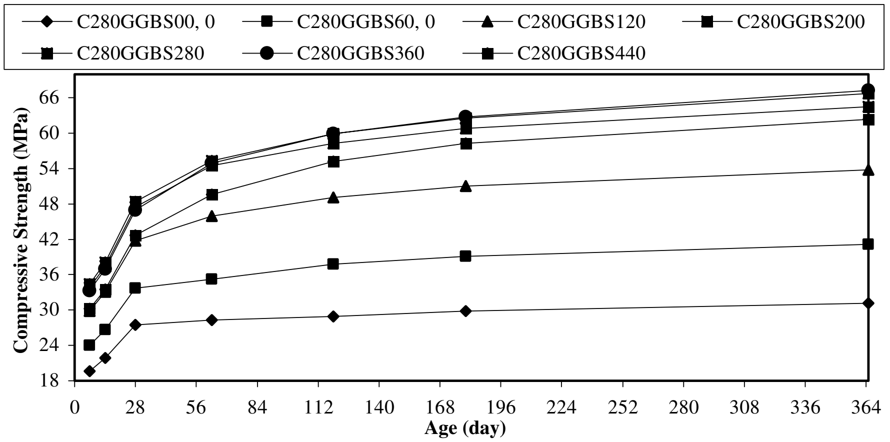

Fig. 4. Compressive strength development of 280 dosage concrete.

3.3. Determination of the optimum content of GGBS in concrete mixtures according to the compressive strength values

Bolomey and Féret strength equations are used to determine the equivalent cement content of GGBS concrete mixtures [26];

$$f_c = K_B\left(\frac{C}{W+h} - a\right) \tag{5}$$

where K_B is the Bolomey coefficient, a is a coefficient depending mainly on time and curing, f_c is the compressive strength of concrete (N/mm^2), C is cement content in concrete (kg/m^3), W is the water content in concrete (kg/m^3), h is the air content in concrete (m^3/m^3).

$$f_c = K_F\left(\frac{c}{c+w+h}\right)^2 \tag{6}$$

where K_F is the Féret coefficient, f_c is the compressive strength of concrete (N/mm^2), c is cement content in concrete (m^3/m^3), w is the water content in concrete (m^3/m^3), h is the air content in concrete (m^3/m^3).

The Bolomey (K_B) and Féret (K_F) coefficients are calculated from the slope of the 28th, 180th and 365th day strength values for the concrete mixtures without GGBS addition. The calculated coefficients are as follows; $K_B = 35{,}367$ MPa (28 days), 38,697 MPa (180 days) and 40,999 MPa (365 days), $K_F = 354{,}559$ MPa (28 days), 384,573 MPa (180 days) and 404,376 MPa (365 days). "a" in Bolomey equation, gives the best correlation with the values of 0.417, 0.424 and 0.430 for 28, 180 and 365 days, respectively.

For the concrete mixtures with GGBS, the Bolomey and Féret equations are converted to Eqs. (7) and (8) and the equivalent cement contents C' and c' are calculated based on the compressive strength values, calculated from test results. C' and c' are the equivalent cement contents. The relation between the equivalent cement content C' and the GGBS content (G) is calculated with Bolomey and Féret strength equations and presented in Figs. 5–9. The relation is defined by an equation in the form of $C' = aG^2 + bG$, which passes through the origin and has a maximum value. Similar $C' = G$ curves with high regression coefficients are obtained by the Bolomey and Féret equations. The equations in the form of $C' = aG^2 + bG$ and regression coefficients (R^2) are given for 365 days in Table 6.

$$f_c = K_B\left(\frac{C+C'}{W+h} - a\right) \tag{7}$$

$$f_c = K_F\left(\frac{c+c'}{c+c'+w+h}\right)^2 \tag{8}$$

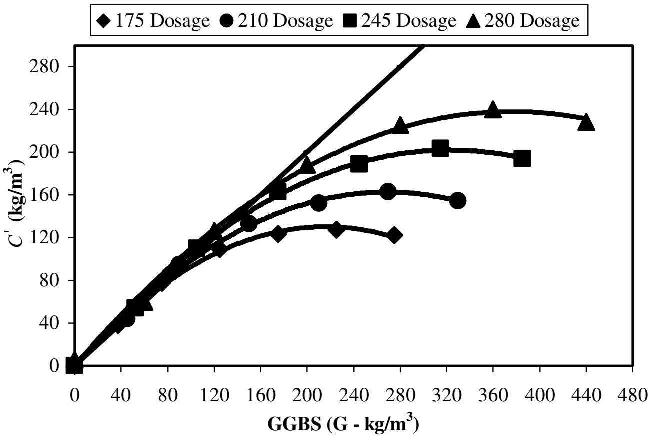

Fig. 5. The relation with equivalent cement content and used GGBS content at the age of 28 days for Bolomey equation.

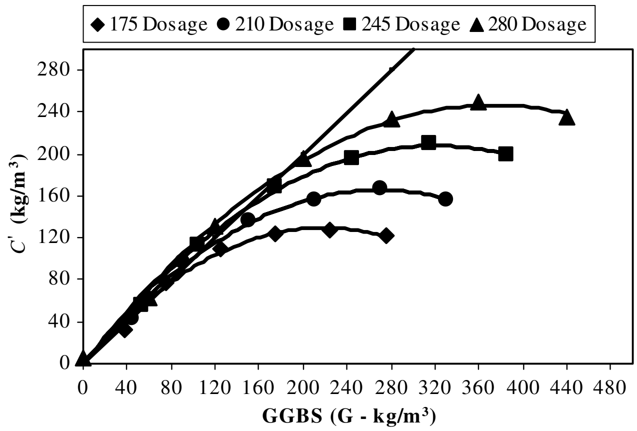

Fig. 6. The relation with equivalent cement content and used GGBS content at the age of 28 days for Féret equation.

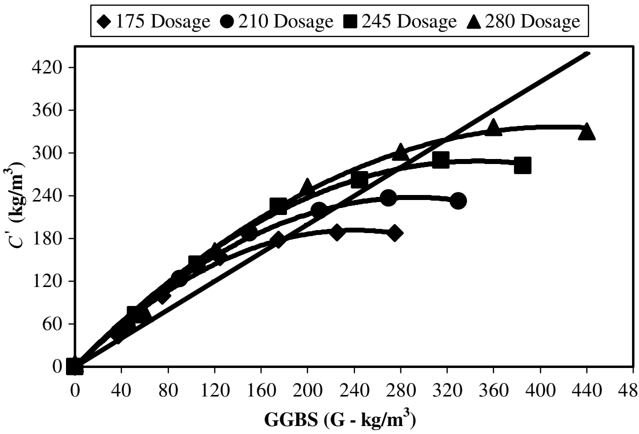

Fig. 7. The relation with equivalent cement content and used GGBS content at the age of 365 days for Bolomey equation.

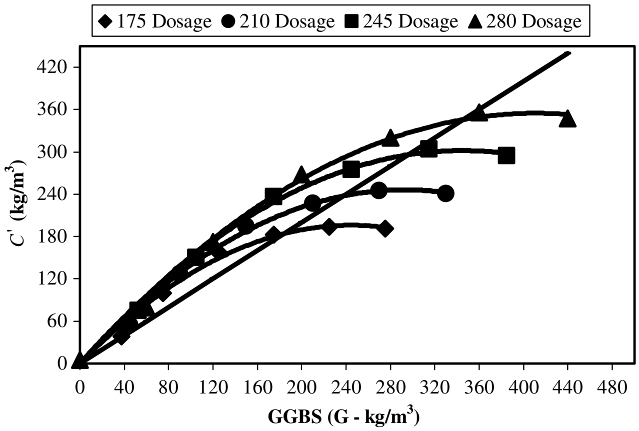

Fig. 8. The relation with equivalent cement content and used GGBS content at the age of 365 days for Féret equation.

In order to find the GGBS content, which yields the highest compressive strength, the peak values of the C'–G curves are calculated by the derivative of these curves.

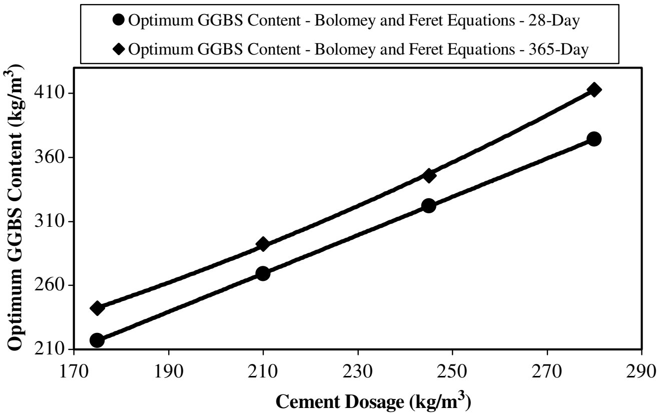

Fig. 9. The optimum GGBS contents at the age of 28, 180 and 365 days compressive strengths (Bolomey and Féret equations).

The GGBS contents below this level are highly effective but the strengths are low. The contents above this level have lower efficiency and lower strength. For this reason, the GGBS content determined by the peak values has the optimum efficiency. Table 7 presents the optimum GGBS contents calculated by the derivative of the C'–G curves. Optimum amounts of GGBS added for compressive strength in concrete with GGBS have been approximately 55–59% of the total amount of binding material. There have been some studies supporting this result in the literature. However, the replacement method is mostly used in these studies. Hogan and Meusel [13] and Meusel and Rose [27] reported that the greatest 28-day strengths are found with blends of 40–50%. Hwang and Lin [17] observed that optimum amount of GGBS for compressive strength is approximately 50% for 90 days.

It can be seen from Fig. 7 that the Bolomey and Féret equations yield similar values of optimum GGBS content. This result validates the used method. The optimum strength values of GGBS concrete mixtures can be calculated by the 28th, 180th and 365th day compressive strength values with Bolomey and Féret equations, depending on the cementitious material contents. Average strength values can be used for the cementitious contents in between the cementitious contents used in the analysis.

The efficiency is defined as the slope of the line connecting any point on the C'–G curve to the origin. By superpose of the C'–G curve and the $C' = G$ line, the GGBS contents, at which the efficiency is 1, is evaluated. At these contents, the GGBS amount has the same performance properties with the equal amount of cement.

The C' equivalent cement content values for the GGBS contents are calculated from the C'–G curves. By calculating the ratio of C' equivalent cement content to GGBS content, the efficiency factor k is found. Figs. 10 and 11 present the efficiency factors depending on GGBS content at for the 28-day-old specimens. It can be seen from these graphs that for the similar cement contents, as the amount of GGBS increase, the efficiency of GGBS decreases.

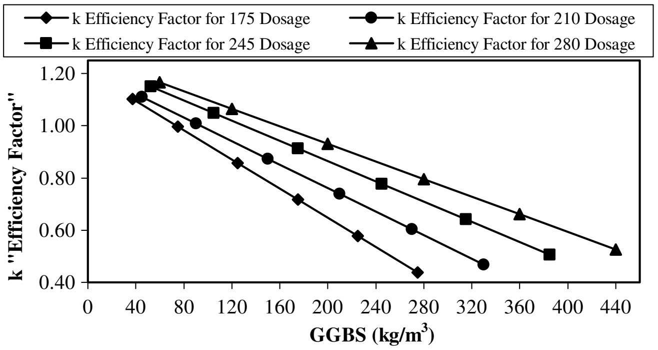

Fig. 10. The relation with efficiency factor and GGBS content at the age of 28 days for Bolomey equation.

Table 6
The equations in the form of $C' = aG^2 + bG$ and regression coefficients (R^2) for 365-day compressive strengths

Cement dosage (kg/m³)		175	210	245	280
Bolomey equation	Equation	$C' = -0.003318G^2 + 1.595491G$	$C' = -0.002790G^2 + 1.629085G$	$C' = -0.002407G^2 + 1.667904G$	$C' = -0.001955G^2 + 1.623471G$
	R^2	0.995	0.996	0.998	0.997
Feret equation	Equation	$C' = -0.003283G^2 + 1.604802G$	$C' = -0.002875G^2 + 1.683002G$	$C' = -0.002543G^2 + 1.752755G$	$C' = -0.002102G^2 + 1.727501G$
	R^2	0.986	0.994	0.997	0.996

Table 7
The optimum GGBS content for 28-, 180- and 365-day compressive strengths

Cement dosage (kg/m³)	Optimum GGBS content for Bolomey equation (kg/m³)			Optimum GGBS content for Féret equation (kg/m³)		
	28 days	180 days	365 days	28 days	180 days	365 days
175	216	234	240	218	237	244
210	269	287	292	269	288	293
245	323	344	346	321	343	345
280	376	408	415	372	404	411

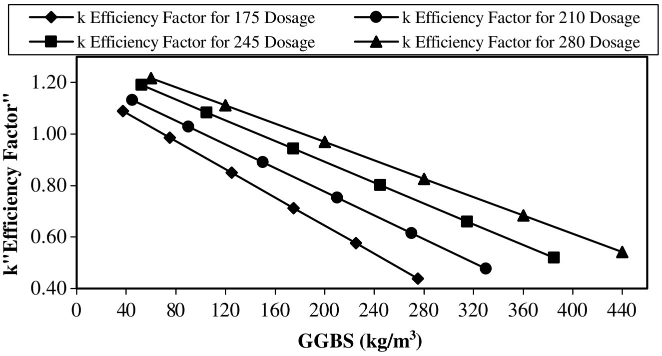

Fig. 11. The relation with efficiency factor and GGBS content at the age of 28 days for Féret equation.

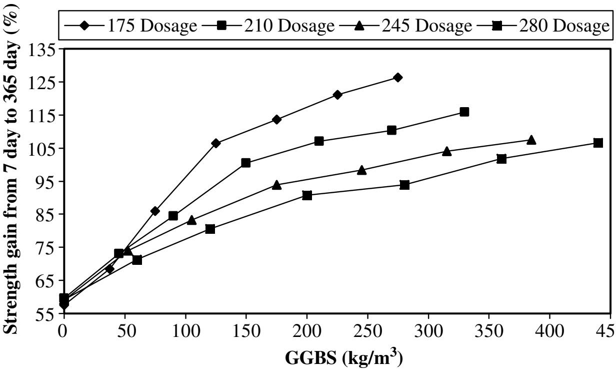

Fig. 13. Strength gain from 7 to 365 day in concrete containing GGBS.

All the curves presented in Figs. 5–10 are second-degree curves, which pass through the origin and a maximum, and comply with the test results. The maximum points for the optimum usage of GGBS contents decrease even tough the GGBS content increase. It can be concluded that, after a certain limit, GGBS cannot be used efficiently as a binder, but rather as filler in the concrete. As the cement content increases, the hydration product calcium hydroxide also increases and more calcium silicate hydrates are formed due to reaction with GGBS. For this reason, GGBS can be used more efficiently.

4. Conclusion

The following conclusions can be drawn from this experimental study:

1. When the water-to-binder ratios of the mixes is taken into account, it can be concluded that as the GGBS content increases, the water-to-binder ratio decreases for the same workability, and thus, the GGBS has positive effects on the workability (Fig. 12).
2. The early age strength of GGBS concretes was lower than the control concretes with the same binder content. However, as the curing period is extended, the strength increase was higher for the GGBS concretes. The reason is that, the pozzolanic reaction is slow and the formation of calcium hydroxide requires time (Fig. 13).
3. The compressive strength of GGBS concrete increases as the GGBS content is increased up to an optimum point, after which the compressive strength decreases. There is an optimum level for the efficient use of GGBS content, which yields the highest strength.
4. The optimum level of GGBS content for maximizing strength is at about 55–59% of the total binder content.
5. After a maximum point C'–G curves decrease, which may be due to the existence of excess GGBS in the medium, which cannot enter into reaction. This indicates that the GGBS, which could not enter into reaction, behave like fine aggregate.

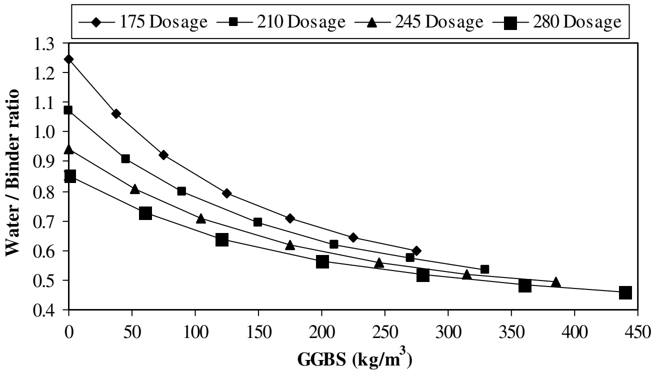

Fig. 12. The relation with GGBS content and water/binding ratio for equal workability.

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