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Effects of bottom ash and granulated blast furnace slag as fine aggregate on abrasion resistance of concrete

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Abstract: Abrasion resistance is one of the most important durability properties of concrete. Especially, highway, airport and industrial floor pavements should be resistant to abrasion. Recently, many research studies have been carried out on the utilization of industrial by-products in concrete. Granulated blast-furnace slag (GBFS) and bottom ash (BA) are two of these by-products. BA is not generally utilized in concrete and has a limited usage. It is mostly dumped, leading to additional costs and environmental problems. On the other hand, both GBFS and BA have potential for concrete production to provide sustainability. They can substitute fine aggregate thanks to their positive effects on concrete durability. Therefore, the aim of this study was to investigate the abrasion resistance of concretes produced with GBFS and BA substituting fine aggregate. Three different concrete series were produced by replacing fine aggregate with GBFS, BA and both of them by mixing them at equal ratios. The replacement ratios of by-products were 10%, 20%, 30%, 40% and 50% by volume. Compressive strength and Bohme abrasion tests were conducted on series. Results were compared to each other. It can be said that abrasion resistance can be improved by these by-products.

Keywords: abrasion resistance; blast-furnace slag; bottom ash; concrete; durability.

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1 Introduction

Concrete is the most common construction material thanks to its advantages such as versatility, low cost, ease of production, high mechanical strength and durability. Fine and coarse aggregates are the main components which constitute the most of concrete volume (75%–85%). Thus, aggregates play an important role in modifying the properties of concrete [1]. Aggregates are generally obtained from natural sources and could result in destruction of the environment when the annual concrete consumption is estimated up to 55 billion m^3 worldwide [2]. No natural resources have infinite reserves. In this situation, the society must be transformed from the consumption-based society to a sustainable society in order to save the natural environment and avoid consumption of natural resources [3, 4]. In this regard, one of the greatest challenges which the concrete industry faces is to focus its objectives towards achieving sustainable development [5]. In this respect, the sustainability concept in construction has recently come into prominence and been applied to the concrete technology. Utilization of waste materials in concrete, presenting many advantages, has come into picture since civil engineering area, construction industry and modern concrete technology are capable of absorbing large amount of wastes and by-products in order to produce contributing concrete products. This is an example of the industrial ecology concept for sustainable future of the world. Thus, it can be said that industrial wastes and by-products can be used as raw materials in other industries [6].

For example, recycled rubber can be utilized in concrete panel production, cementitious sheets for sealing systems and other concrete products, such as concrete floors, walls and roof tiles [7–11]. Waste marble is considered in concrete, concrete interlocking paving block production and ceramic production [12–16]. Waste ferrochromium slag is also recycled in concrete as aggregate [4, 6]. Recycled concrete aggregate is also utilized in concrete production [17–20]. Copper slag is one of the other wastes or by-product aggregates that have been used in concrete [21, 22]. As mentioned, awareness of their significant impacts on natural resource consumptions and pollutant emissions is increasing. There is a high emerging demand for environmentally friendly construction and building materials. In this respect, “green” concretes have become one of major focuses in concrete science for environmental improvements [23].

Bottom ash (BA) remains a waste from combustion of coal in thermal power plants. Its properties depend on the type, source and fineness of coal burned. BA, in granular structure, is accumulated at the bottom of the combustion chamber. About 100,000 tons of BA is generated per year at only Çatalağzı Thermal Power Plant in Zonguldak Province, Turkey. Relatively a very few detailed studies have been conducted on the use of BA as a low-cost replacement material in the production of concrete. Some researchers have reported studies dealing with utilization of BA in concrete as cementitious supplementary material [24, 25] or as a partial replacement of fine aggregate [26–29]. Iron-steel industry produces slags as by-products. Molten slag is produced during the manufacturing of pig iron. When it is cooled immediately, it forms a glassy amorphous material used as a cementitious material called granulated blast-furnace slag (GBFS). If it is cooled slowly, it forms a crystalline structure which is generally used as aggregates (blast-furnace slag) [30]. However, GBFS is commonly used in cement production in ground form rather than being utilized as fine aggregate [31].

Structures such as concrete highways, pedestrian walk pavements, industrial floors and hydraulic structures are exposed to abrasive forces. Abrasion of the concrete surface leads to the loss of surface quality. Only a few papers have reported the abrasion resistances of concrete containing BA and GBFS fine aggregates. Recently, although fly ash (FA), BA and GBFS have been used in cement and concrete technologies as indicated above, still their usages are limited as aggregate and need further studies. Thus, in this study, the combined effects of FA admixture, BA and GBFS fine aggregates on compressive strengths and abrasion resistances are investigated. Consequently, it can be said that abrasion-resistant concrete types are attempted to be designed and developed in order to construct structures such as sport area floor, pedestrian or road pavements and so on. Besides, because industrial floor concretes expose to extreme mechanical loads, the surfaces of these concrete types have to be smooth and hardened in order to avoid surface losses because of abrasion. A coating cover layer is obtained by proper finishing and using some surface hardening chemical admixtures to prevent abrasion losses. These applications lead to additional costs, long construction time and hard workmanship in construction. Therefore, using abrasion-resistant concrete types produced with by-product aggregates such as GBFS and/or BA could provide production easiness, time savings and decreased additional costs.

2 Materials and methods

2.1 Cement

The cement used was Portland cement CEM I 42.5R (Set Cement Factory, Ankara, Turkey). It complies with the requirement of the European Standard EN 197-1 [32]. This type of cement was selected because of its common usage and availability in Turkish Concrete Industry. Therefore, this type of cement can also be available easily to produce GBFS and BA concretes with other regular concrete components, such as available mineral, chemical admixture and ordinary natural aggregates, which are commonly used in Turkish Concrete Industry. In this way, these types of concretes can be used widely in order to gain such advantages which are mentioned in the previous section. The properties of cement are given in Table 1.

2.2 Fly ash

FA was F-type ash according to American Society for Testing Materials (ASTM) C 618 [33]. FA was obtained from Çatalağzı Thermal Power Plant, Zonguldak, Turkey. Its chemical composition is given in Table 2. The Blaine fineness, which is defined as a measure of the particle size or fineness of cement and supplementary cementitious materials, was 3820 cm^2/g. The specific gravity

Table 1: Properties of cement.

Composition (%)		Physical properties	
SiO_2	20.52	Specific gravity (g/cm^3)	3.16
Al_2O_3	5.11	Specific surface (cm^2/g)	3300
Fe_2O_3	2.84	Retaining on 32 μm (wt.%)	21
CaO	63.62	Retaining on 90 μm (wt.%)	0.8
MgO	1.9	Retaining on 200 μm (wt.%)	0.1
SO_3	3	Initial setting time (min)	190
		Final setting time (min)	225
C_3S	53.13	Volume expansion (mm)	1
C_3A	8.74		
Cl^-	0.72		
Loss on ignition	1.96		

Table 2: Chemical composition of fly ash [57].

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)	Na_2O (%)	KK (%)	Cl^- (%)
58.69	25.10	5.80	1.49	2.22	0.12	4.04	0.59	1.28	0.013

was 2.02 g/cm^3. Cement paste is highly crucial because it is an agent to carry aggregates [4]. Thus, FA was used to increase paste volume. FA reduces cement demand in concrete. As a by-product of coal power plants, FA increases mechanical and durability properties such as freeze-thaw resistance, sulfate resistance, alkali-silica reaction, chloride penetration and abrasion resistance when it is used as a supplementary cementitious material in mortar and concrete. In addition, shrinkage and permeability of hardened concrete are decreased due to the filling of micropores and voids. FA is common in concrete technology because it also reduces chloride penetration and steel corrosion in concrete [34–36]. However, if FA is not utilized, it leads to environmental pollution and very high cost of storage of FA.

The usage of industrial waste materials and/or by-products in concrete in regard to both environmental pollution and the positive effect on a country's national economy is beyond dispute [34]. In Turkey, the annual FA production is about 18 million tons, and it is more than the production of the rest of all industrial wastes and by-products [37]. In India, approximately 80 million tons of FA is generated each year [38]. The current annual production of FA worldwide is estimated to be approximately 600 million tons [6, 39]. Pozzolanic activity indexes of the used FA at 7, 28 and 90 days were as 75%, 80% and 93%, respectively.

2.3 Aggregates

2.3.1 Natural coarse and fine aggregates

Plain concrete was produced by using crushed aggregate of the maximum 7 mm nominal size. Natural river aggregates, which are locally available in Filyos river of Zonguldak, were used. Natural river sand (NRS) with a size range of 0–4 mm and natural coarse aggregate (NCS) with a range of 4–7 mm were used. Sieve analyses of NRS and NCS are presented in Table 3. Specific gravity, water absorption, and loose and dry unit weights were determined according to ASTM C 127 [40], ASTM C128 [41] and ASTM C29 [42] standards. Mixing ratios of NRS and NCS, in total aggregate volume, were 40% and 60%, respectively.

Table 3: Size distributions of aggregates.

Sieve size (mm)	Passing (%)	
	NRS	NCS
8	100	99.57
6.7	100	93.68
4.75	100	66.99
4	66.47	66.47
3.35	60.12	0
2.36	32.05	0
1.7	21.52	0
1.18	11.78	0
0.6	6.31	0
0.3	4.14	0
0.1	0.00	0

2.3.2 GBFS and BA fine aggregates

In this study, fine GBFS and BA aggregates (see Figure 1) were used. BA usually consists of high amounts of SiO_2 and Al_2O_3, but lower amounts of CaO. The GBFS consists of high amounts SiO_2, Al_2O_3 and CaO and low amounts of MgO. They have rough and porous surfaces, leading to the better bonding to cement paste and higher abrasion resistances [26, 27]. BA was obtained from Çatalağzı Thermal Power Plant, Zonguldak, Turkey. GBFS was obtained from Ereğli Iron-Steel Works Company-Factory, Zonguldak, Turkey. Sieve analyses of BA and GBFS fine aggregates are presented in Table 4. The physical properties of all aggregate types are shown in Table 5. Chemical composition of GBFS is given in Table 6. Chemical composition of BA is presented in Table 7. The pozzolanic activity indexes of BA at 7, 28 and 90 days were 77%, 86% and 97%, respectively. Residual above 45 µm sieve was about 25.8%.

2.4 Superplasticizer

GBFS and BA increase water demand of concrete due to their high specific surface areas and pretty rough structure of their surfaces. Therefore, polycarboxylate-based superplasticizer (SP) was added to the mixture at the ratio of 0.7% of cement content by weight to provide desired workability. It has a specific gravity of 1.08, pH=5.7 and solid content of 40 wt.%.

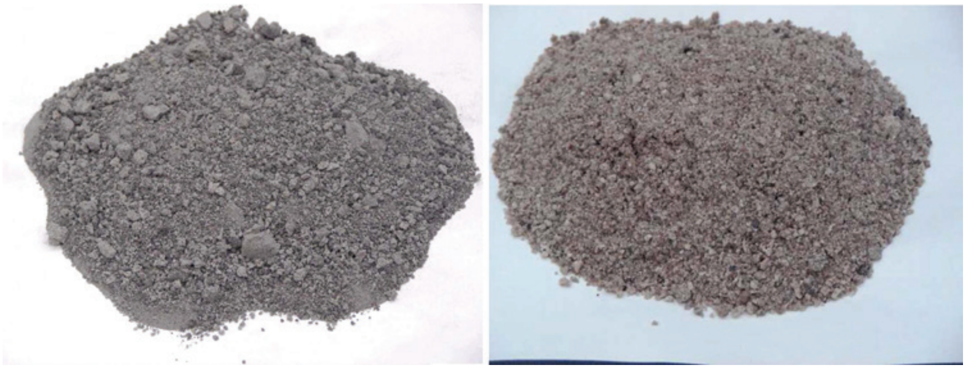

Figure 1: BA (left) and GBFS (right) fine aggregates.

Table 4: Size distributions of GBFS and BA.

Sieve size (mm)	Passing (%)	
	GBFS	BA
4	99.38	94.03
3.35	98.2	91.9
2.36	92.16	86.23
1.7	77.1	76.97
1.18	62.26	61.7
0.6	17.72	36.63
0.3	4.94	–
0.212	2.84	–
0.1	0.8	6.57
0.075	0.44	3.8
0.045	0.12	1.07

2.5 Mix proportions

Mix design was obtained according to the absolute volume method. Cement content and water/cement ratios were kept constant as 350 kg/m^3 and 0.48, respectively. FA was used at the constant ratio of 21% of cement content in all mixture. When FA was added, the total water/binder ratio was also kept as 0.58. Fine NRS aggregate was replaced with by-product aggregates (GBFS and BA) at the ratios of 10%, 20%, 30%, 40% and 50% by volume. The dosage of SP was 0.7% of the cement content of concrete by weight. It was assumed that approximately 1.5% air has been trapped in fresh concrete. The concrete composition is given in Table 8. Concrete series were coded as A, B and

Table 5: Properties of aggregates used.

Property	Unit	NRS	NCS	GBFS	BA	FA
Loose unit weight	kg/m^3	1930	–	1052	620	870
Rodded unit weight	kg/m^3	1950	–	1236	660	1110
Specific gravity	(g/cm^3)	2.60	2.65	2.08	2.59	2.02
Water absorption	%	11.3	1.73	10	12.1	–
Fine material ratio	%	4	1.11	3	7	–
Organic material (NaOH solution)	Color	Light yellow	–	Light yellow	–	–

Table 6: Chemical composition of GBFS.

SiO_2 (%)	CaO (%)	MgO (%)	Al_2O_3 (%)	Na_2O (%)	S (%)	MnO (%)	TiO_2 (%)	Fe (%)	P_2O_3 (%)
35.09	37.79	5.50	17.54	0.30	0.66	0.83	0.68	0.70	0.37

Table 7: Chemical composition of BA [26].

SiO_2 (%)	CaO (%)	MgO (%)	Al_2O_3 (%)	Na_2O (%)	K_2O (%)	Fe_2O_3 (%)	SO_3 (%)	Cl^- (%)	Loss on ignition (%)
57.9	2	3.2	22.6	0.086	0.604	6.5	0.08	0.0064	1.67

Table 8: Mixture proportions for 1 m³.

Code	Mixes (by volume)	Cement (kg/m³)	Water (kg/m³)	FA (kg/m³)	NCS (kg/m³)	NRS (kg/m³)	GBFS (kg/m³)	BA (kg/m³)	SP (kg/m³)
RF	Control	350	167	35	1120	720	0	0	2.45
A1	10% GBFS	350	167	35	1120	648	72	0	2.45
A2	20% GBFS	350	167	35	1120	576	144	0	2.45
A3	30% GBFS	350	167	35	1120	504	216	0	2.45
A4	40% GBFS	350	167	35	1120	432	288	0	2.45
A5	50% GBFS	350	167	35	1120	360	360	0	2.45
B1	10% BA	350	167	35	1120	648	0	72	2.45
B2	20% BA	350	167	35	1120	576	0	144	2.45
B3	30% BA	350	167	35	1120	504	0	216	2.45
B4	40% BA	350	167	35	1120	432	0	288	2.45
B5	50% BA	350	167	35	1120	360	0	360	2.45
C1	5% GBFS+5% BA	350	167	35	1120	648	36	36	2.45
C2	10% GBFS+10% BA	350	167	35	1120	576	72	72	2.45
C3	15% GBFS+15% BA	350	167	35	1120	504	108	108	2.45
C4	20% GBFS+20% BA	350	167	35	1120	432	144	144	2.45
C5	25% GBFS+25% BA	350	167	35	1120	360	180	180	2.45

C with respect to the by-product fine aggregate types and replacement ratios. GBFS and BA were also mutually combined at equal ratios while replacing fine aggregate at the ratios of 10%, 20%, 30%, 40% and 50% by volume. Besides, these combined by-product series were coded as C series and their properties were also investigated.

2.6 Method

The concrete mixtures were prepared in a laboratory mixer with a capacity of 60 dm³. The mixing procedure was as follows. The materials were placed in the mixer in the following sequence: first, coarse aggregates and fine aggregates were placed, and then cement was added. After that, this dry mixture was initially mixed for 1 min and 90% of water was added. After 1.5 min of mixing of this wet mixture, the rest of the water mixed with the SP was added to the mixture. Then, for each concrete series, three 70 mm cubes were cast in order to conduct compressive strength tests. After casting, the concrete specimens were covered with wet burlap and polyethylene sheets, and kept in the laboratory at room temperature for 24 h. After demolding, the concrete specimens were immersed into lime saturated water until the testing day. Curing was done in accordance with ASTM C511 [43]. It is well recognized that adequate curing of concrete is very important, not only to reach the desired compressive strength but also to produce durable concrete. After the curing process, all the specimens were stored under laboratory conditions at 20°C and 65% relative humidity for 24 h, and then tested. The compressive strength tests were carried out in accordance with ASTM C39 [44] at 28 and 90 days.

In the abrasion test, while a disk is rotating around a vertical axis, an abrasive powder abrades the specimen. Cubic specimens with the sizes 70×70×70±1.5 mm (50.4 cm² cross-sectional area) were used for determination of abrasion resistance in 28 days according to Turkish standard TS 699 [45]. TS 699 is considered as an alternative to ASTM C779 [46]. According to TS 699, the abrasion system has a steel disk with the diameter of 750 mm, a counter, and a lever, applying a rotating speed of 30 cycles/min. The testing device is shown in Figure 2. In order to obtain abrasion, 20±0.5 g abrasive powder, corundum (crystalline Al_2O_3), was spread on the disk, and the specimens were then positioned to its place on the disk; 5 kg load was applied to each specimen, and the disk was

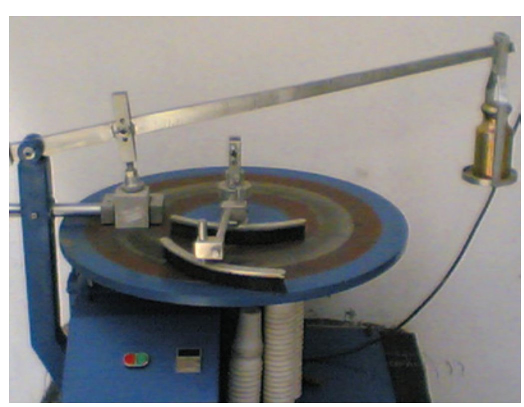

Figure 2: Abrasion test apparatus (Bohme method).

rotated for four periods – a period was equal to 22 cycles. After each period, the concrete cubic sample was rotated around its vertical axis at an angle of 90°. This procedure was repeated for each of the four edges of the same surface of the concrete specimen. In this manner, all four edges of the same surface of the concrete cubic specimen faced the abrasion powder. In other words, the same concrete surface was subjected to abrasion from all its four edges. Abrasion resistances were calculated after 88 traversals over the same track. Then, volume loss was considered as a measure on the 50 cm^2 surface area due to abrasion and compared with the limit values specified in TS 699. All specimens of each series were exposed to this Bohme abrasion test.

3 Results and discussion

Figure 3 shows the abrasion resistances of concrete series. When the GBFS ratio increases in the mixtures of series A, the abrasion loss decreases. It can be said that GBFS increases abrasion resistance. However, although a marginal effect was expected before the test, it was not observed. The reason may be the decrease in compressive strength with the increase in the replacement ratio of GBFS. Concretes containing GBFS still endure the abrasive effect. After the 20% replacement ratio of BA is deployed, the abrasion resistance is close to that of A series. When the combined effect of GBFS and BA is considered, it can be said that the abrasion resistance increases. Specimens C1 and C2 are highly resistive to abrasion. The others also present a better performance compared to the results of A series. When GBFS and BA are combined mutually and used as fine aggregate, concrete with less porosity can be achieved. This is why concretes with a combination of them have a better abrasion resistance. In all series, volume losses due to the abrasion are under the upper limit value, 13 $cm^3/50\ cm^2$, given as the conformity criteria in TS 699. Yüksel and Bilir reported that interlocking paving blocks and curbs with GBFS are resistant to the abrasion [26]. In their study, an increase in the replacement ratios of GBFS fine aggregate in paving blocks and curbs decreases their compressive strengths. As known, water reducer admixtures when used in concrete increase both compressive strength and abrasion resistance of concrete [47]. In this study, SP used decreases water demand of BA resulting in high abrasion resistance. Additionally, FA can contribute to the increase in the abrasion resistance of concrete as mentioned in previous studies [48–50]. GBFS and BA fine aggregates are pozzolans that contain higher contents of SiO_2, Al_2O_3 and Fe_2O_3. Additionally, lime-based (CaO) natural aggregates are known to be less resistant to abrasion. In this manner, such pozzolan by-product aggregates generally increase the abrasion resistance. Thus, it can be said that these by-product aggregates increased the abrasion resistance for lower replacement ratios. Then, the porosities of all series increased with the increase in the replacement ratio due to the porous surfaces and gradations of these by-product aggregates. The compressive strength results verify this statement. As the replacement ratio increases, the concrete porosity increases and the compressive strength decreases as below. On the other hand, FA also contributes to both higher compressive strength and higher abrasion resistance results. FA leads to the lower porosity in concrete due to its pozzolanic reaction and increases the positive effects of GBFS and/or BA aggregates on both compressive strength and abrasion resistance of concrete.

The compressive strength of A series is presented in Figure 4. As seen from this figure, GBFS addition decreases the compressive strength at 28 and 90 days.

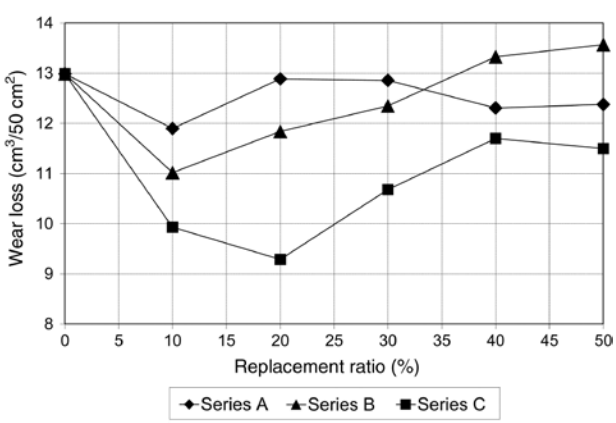

Figure 3: Abrasion losses of concrete series.

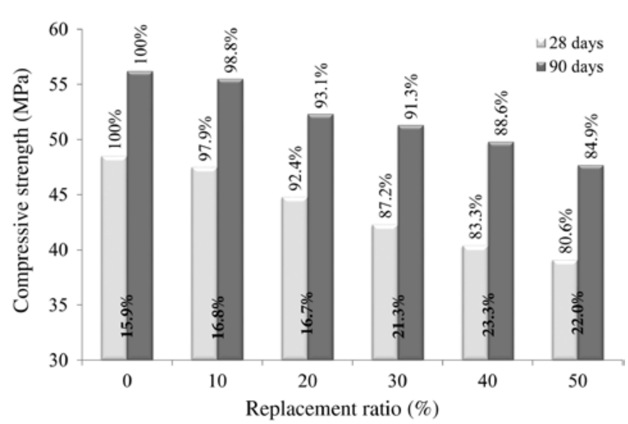

Figure 4: Compressive strength of series A.

Compressive strength decreases are up to 19.4% at 28 days for the 50% replacement ratio of GBFS when compared to that of control, A series. It is 15.1% at 90 days. Differences between 28 and 90 days are given on the bars in Figure 4. It is clearly seen that compressive strength losses vary between 15.9% and 23.3% depending on the GBFS replacement ratio. The reason can be said as porous structure and low compressive strength of GBFS fine aggregate compared to fine NRS. This was also reported in previous studies [26, 27, 51–54]. On the other hand, compared to the previous results in which GBFS replaced natural sand by weight, GBFS replacing fine aggregate by volume seems to be causing lower compressive strength losses and a more relative dense structure.

The compressive strength of B series is presented in Figure 5. As seen from this figure, BA replacement decreases the compressive strength at 28 and 90 days. Compressive strength decreases are up to 24.7% at 28 days for the 50% replacement ratio of BA fine aggregate when compared to that of control, A series. It is 27.6% at 90 days. Differences between 28 and 90 days are given on the bars in Figure 5. It is clearly seen that compressive strength losses vary between 15.9% and 25.7% depending on BA replacement. BA fine aggregate has similar effects to GBFS fine aggregate on the compressive strength of concrete [26, 27, 51, 54]. According to the sieve analyses of both by-product aggregates in previous studies, the maximum aggregate size of BA fine aggregate is about 2 mm, which means that it is finer than GBFS fine aggregate [26, 54]. Therefore, it is capable to decrease the porosity of concrete. On the other hand, it may decrease the workability and change the gradation of the fine aggregate package compared to GBFS and may decrease compressive strength as seen from Figures 4 and 5. Consequently, both these effects lead to similar compressive strength losses in B series and A series.

The compressive strength of C series is presented in Figure 6. As seen from this figure, GBFS+BA replacement decreases the compressive strength at 28 and 90 days. Compressive strength decreases are up to 18.6% at 28 days for the 50% replacement ratio of GBFS+BA replacement by volume (25% BA+25% GBFS fine aggregate package) when compared to that of control, A series. It is 22.6% at 90 days. Differences between 28 and 90 days are given on the bars in Figure 6. It is clearly seen that compressive strength losses vary between 15.9% and 17.9% depending on GBFS+BA replacement. When finer BA is mixed with GBFS at equal ratios by volume, it may lead to a denser and a better graded fine aggregate package [27, 54]. In this manner, the compressive strength losses, with respect to the by-product replacement ratio, are lower than B series but similar to A series.

Such strength decreases compared to the ordinary concrete have been reported many times when waste or by-product aggregates, which have lower strengths and porous microstructures, are used in mortar and concrete production [51–56]. However, it can also be seen from the obtained compressive strength test results that all series including control series (A series) have compressive strengths above 45 MPa. Consequently, when compared to the previous studies [51–56], it can be said that GBFS, BA and GBFS+BA fine aggregate replacements by volume up to the ratios of 50% lead to higher compressive strengths, lower pore volume and lower permeability than do replacements by weight [51–56]. In addition to this, the structural concrete can also be produced by replacing natural fine aggregate with these by-products. As mentioned previously, using wastes have many advantages in the means of sustainable development, concrete production costs, environmental issues, energy and natural resource conservation. It seems that the structural concrete can be designed and produced by replacing fine aggregate with these by-products even

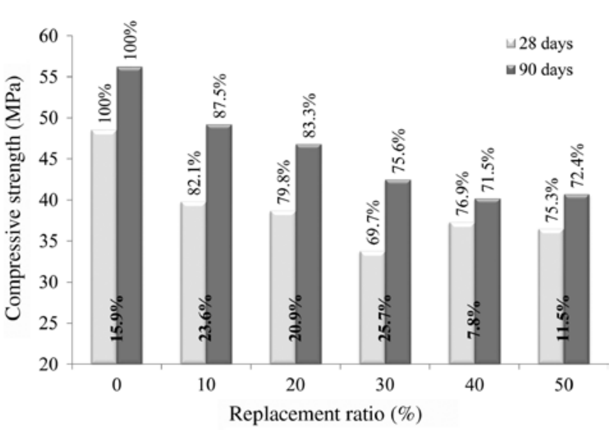

Figure 5: Compressive strength of series B.

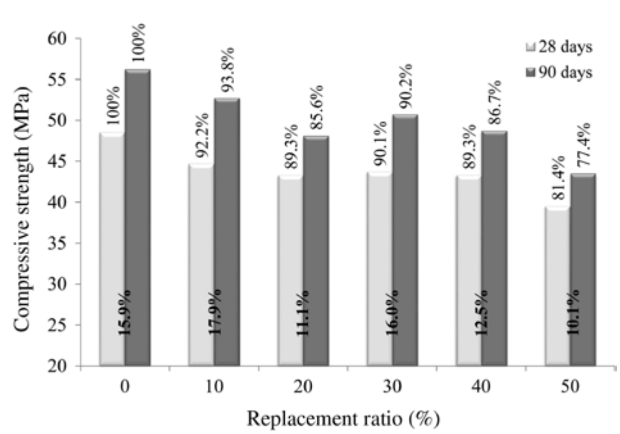

Figure 6: Compressive strength of series C.

up to replacement ratios of 50% by volume. It means that these by-products can take place of natural sand and fine aggregate and the mentioned advantages can be improved for concrete industry.

An interesting result is observed from these figures. Opposite to what was expected, abrasion resistance increases while compressive strength decreases. It can also be said that while compressive strength decreases, abrasion does not change significantly. Finally, it can be concluded that GBFS and BA fine aggregates increase the abrasion resistance of concrete thanks to its mechanical, physical and chemical properties.

4 Conclusion

The civil engineering construction industry seems to be capable of absorbing large amounts of wastes and by-products in order to produce useful products. Industrial by-products can be used as raw materials in other industries as mentioned in many previous studies and also this current study related to the industrial ecology concept. In this study, GBFS, BA and FA by-products were used in concrete as fine aggregate to produce "green concrete" as a durable, structural and environmentally friendly concrete. They decrease the compressive strength of concrete. However, sufficient compressive strengths for all by-product fine aggregates (A, B and C series) can be obtained. Therefore, even structural concrete types can be produced. Besides, when GBFS, BA and both of them (GBFS+BA) are used as fine aggregates in concrete production, the abrasion resistances of concretes increase. Volume losses, due to abrasion, of all concrete series (A, B and C series) containing GBFS, BA and GBFS+BA are under the specified limit value, 13 $cm^3/50\ cm^2$, mentioned in TS 699. In conclusion, these by-product aggregate types improve the abrasion resistance and durability of concrete thanks to their physical, chemical and mechanical properties.

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References

[1] de Larrard F, Belloc A. *ACI Mater. J.* 1997, 94, 417–425.
[2] Mehta PK, Monteiro PJM. *Concrete, Microstructure, Properties and Materials*, Prentice Hall: New York, USA, 2001, p. 17.
[3] Pelisser F, Zavarise N, Longo TA, Bernardin AM. *J. Clean. Prod.* 2011, 19, 757–763.
[4] Gencel O, Koksal F, Ozel C, Brostow W. *Constr. Build. Mater.* 2012, 29, 633–640.
[5] Duran-Herrera A, Juarez CA, Valdez P, Bentz DP. *Cement Concrete Compos.* 2011, 33, 39–45.
[6] Uygunoglu T, Topcu IB, Gencel O, Brostow W. *Constr. Build. Mater.* 2012, 30, 180–187.
[7] Fattuhi NI, Clark LA. *Constr. Build. Mater.* 1996, 10, 229–236.
[8] Li G, Garrick G, Eggers J, Abadie C. *Compos. B Eng.* 2004, 35, 305–312.
[9] Siddique R, Naik TR. *Waste Manage.* 2004, 24, 563–569.
[10] López-Gayarre F, López-Colina C, Serrano-López MA, López-Martinez A. *Constr. Build. Mater*. 2013, 40, 1193–1199.
[11] López-Gayarre F, López-Colina C, Serrano-López MA, Domingo-Cabo A. *Construct. Build. Mater*. 2014, 53, 260–266.
[12] Alyamac KE, Ince R. *Construct. Build. Mater.* 2009, 23, 1201–1210.
[13] Topcu IB, Bilir T, Uygunoglu T. *Constr. Build. Mater.* 2009, 23, 1947–1953.
[14] Saboya Jr F, Xavier GC, Alexandre J. *Constr. Build. Mater.* 2007, 21, 1950–1960.
[15] Gencel O, Ozel C, Koksal F, Erdogmus E, Martínez-Barrera G, Brostow W. *J. Clean. Prod.* 2012, 21, 62–70.
[16] Zelic J. *Cement Concrete Res.* 2005, 35, 2340–2349.
[17] Topcu IB, Sengel S. *Cement Concrete Res.* 2004, 34, 1307–1312.
[18] Poon CS, Shui ZH, Lam S, Fok H, Kou SC. *Cement Concrete Res.* 2004, 34, 31–36.
[19] Tabsh SW, Abdelfatah AS. *Constr. Build. Mater.* 2009, 23, 1163–1167.
[20] Marinkovic S, Radonjanin V, Malesev M, Ignjatovic I. *Waste Manage.* 2010, 30, 2255–2264.
[21] Shi C, Meyer C, Behnood A. *Resour. Conserv. Recycl.* 2008, 52, 1115–1120.
[22] Khanzadi M, Behnood A. *Constr. Build. Mater.* 2009, 23, 2183–2188.
[23] Chau CK, Yik FWH, Hui WK, Liu HC, Yu HK. *J. Clean. Prod.* 2007, 15, 1840–1851.
[24] Kurama H, Kaya M. *Constr. Build. Mater.* 2008, 22, 1922–1928.
[25] Kula I, Olgun A, Sevinc V, Erdogan Y. *Cement Concrete Res.* 2002, 31, 491–494.
[26] Yüksel İ, Bilir T. *Constr. Build. Mater.* 2007, 21, 686–694.
[27] Yüksel İ, Bilir T, Özkan Ö. *Build. Environ.* 2007, 42, 2651–2659.
[28] Bai Y, Darcy F, Basheer PAM. *Constr. Build. Mater.* 2005, 19, 691–697.
[29] Cheriaf M, Rocha JC, Pera J. *Cement Concrete Res.* 1999, 29, 1387–1391.
[30] Li G, Zhao X. *Cement Concrete Compos.* 2003, 25, 293–299.
[31] Richardson IG, Groves GW. *J. Mater. Sci.* 1992, 27, 6204–6212.
[32] TS EN 197-1, *General Purpose Cements-Part 1: General Purpose Cements – Components, Properties and Conformity Criteria*, Turkish Standards Institute: Ankara, 2002 (in Turkish).
[33] ASTM C618, *Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, Annual Book of ASTM Standards*, ASTM: Pennsylvania, 2008.
[34] Topçu IB, Canbaz M. *Constr. Build. Mater.* 2007, 21, 1486–1491.
[35] Chalee W, Ausapanit P, Jaturapitakku C. *Mater. Design* 2010, 31, 1242–1249.
[36] Gencel O, Brostow W, Tea D, Thedford M. *Compos. Interf.* 2011, 18, 169–184.
[37] Yazıcı H. *Constr. Build. Mater.* 2008, 22, 456–462.

[38] Siddique R. *Cement Concrete Res.* 2003, 33, 1877–1881.
[39] Ahmaruzzaman M. *Prog. Energy Combust. Sci.* 2010, 36, 327–363.
[40] ASTM C127, *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate, ASTM Annual Book of ASTM Standards*, ASTM: Pennsylvania, 2007.
[41] ASTM C128, *Standard Test Method for Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate*, *ASTM Annual Book of ASTM Standards*, ASTM: Pennsylvania, 2007.
[42] ASTM C29, *Standard Test Method for Bulk Density (Unit Weight) and Voids in Aggregate, Annual Book of ASTM Standards*, ASTM: Pennsylvania, 2007.
[43] ASTM C511, *Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes*, *Annual Book of ASTM Standards*, ASTM: Pennsylvania, 2009.
[44] ASTM C39, *Test for Compressive Strength of Cylindrical Concrete Specimens*, *Annual Book of ASTM Standards*, ASTM: Pennsylvania, 2001.
[45] TS 699, *Natural Building Stones – Methods of Inspection and Laboratory Testing*, Turkish Standards Institute: Ankara, 2009 (in Turkish).
[46] ASTM C779, *Standard Test Method for Abrasion Resistance of Horizontal Concrete Surfaces*, *Annual Book of ASTM Standards*, ASTM: Pennsylvania, 2000.
[47] Ghafoori N, Bulholc J. *J. Mater. Civil Eng.* 1996, 8, 128–137.
[48] Richardson MG. *Fundamentals of Durable Reinforced Concrete*, Spon Press: London, 2002.
[49] Atış CD. *J. Mater. Civil Eng.* 2002, 14, 274–277.
[50] Atış CD. *J. Mater. Civil Eng.* 2003, 15, 408–410.
[51] Yüksel İ, Özkan Ö, Bilir T. *ACI Mater. J.* 2006, 103, 203–208.
[52] Topçu İB, Bilir T. *ACI Mater. J.* 2010, 107, 48–56.
[53] Topçu İB, Bilir T. *ACI Mater. J.* 2010, 107, 545–553.
[54] Bilir T. *Constr. Build. Mater.* 2012, 26, 730–734.
[55] Topçu İB, Bilir T. *Mater. Design* 2010, 31, 4088–4097.
[56] Topçu İB, Boğa AR, Bilir T. *Waste Manage.* 2008, 28, 878–884.
[57] Türker P, Erdoğan B, Katnaş F, Yeğinobalı A. *Classification and Properties of Fly Ashes in Turkey*, Turkish Cement Manufacturers Association: Ankara, 2003 (in Turkish).