Environ Monit Assess (2019) 191: 560
https://doi.org/10.1007/s10661-019-7741-4

The possibility of fly ash and blast furnace slag disposal by using these environmental wastes as substitutes in portland cement

Oguzhan Yavuz Bayraktar

Received: 22 April 2019 / Accepted: 6 August 2019 /

Abstract The possibility of disposing of fly ash (FA) and blast furnace slag (BFS), which are environmental wastes, by using them as substitutes in portland cement was examined in this study. Portland cement (CEM I), FA, BFS, CEN standard sand, and water were used in the production of mortars. Blended cements were obtained by substituting FA, BFS, and a mixture of FA and BFS (FABFS) at 5.0%, 10.0%, 15.0%, and 20.0% ratios in portland cement. Physical (Blaine area, density, initial and final setting time, and fineness), mechanical (flexural strength and compressive strength), radiation permeability (determination of linear absorption coefficient) and high-temperature experiments were performed on the FA, BFS, and FABFS samples. Mortar prism samples with a size of 40 × 40 × 160 mm were obtained using these cements. The samples were exposed to five temperatures: 20, 150, 300, 700, and 900 °C. Mortar samples kept at 20 °C were used as references. A total of 390 samples were studied under air cooling (spontaneous cooling at 20 ± 2 °C in laboratory environment). After the mortar samples reached at room temperature, flexural strength and compressive strength tests were carried out on the 28th and 90th days. The test results showed that FA, BFS, and FABFS can be used as pozzolanic additives in cement mortars both alone and together and can be applied in buildings with a high risk of fire up to certain temperature values. The sample with the highest linear absorption coefficient was the FABFS sample, and as the sample with the lowest radiation permeability, it was determined to be appropriate for use in buildings that are exposed to radiation effects.

Keywords Blast furnace slag · Fly ash · High temperature · Portland cement · Radiation permeability

Introduction

Today, rapid increases in population, the rapid consumption of energy resources, and waste disposal problems have led scientists to seek new solutions. By considering waste as a raw material source, reusing used raw materials has gained great importance and has led countries to effectively use and improve energy (Brooks and Cetin 2012; Yilmaz 2012; Cetin 2013a, b, 2015a, b; Kaya et al. 2018). The problem of rapid consumption of natural resources (raw materials and energy) brings significant pollution problems. Many countries and international organizations are trying to minimize these losses and reuse wastes under new regulations (Bilgin 2010; Cetin et al. 2012a, b; Cetin 2016; Cetin 2017; Varol et al. 2019; Cetin et al. 2018). Considering all these problems, waste materials that create storage problems can be reused, and thus, environmental protection will be achieved while decreasing the production costs of related products (Brooks and Cetin 2012; Yiğiter 2014; Cetin 2013a, b, 2015a, b; Kaya et al. 2018). Recycling is a long-term economic investment.

O. Y. Bayraktar (✉)
Faculty of Engineering and Architecture, Department of Civil Engineering, Kastamonu University, Kuzeykent, Kastamonu, Turkey
e-mail: obayraktar@kastamonu.edu.tr

Economic problems can increase with decreased raw materials and the rapid consumption of natural resources. The recycling process has positive effects on the economy in this case. Reducing the consumption of energy and natural resources is of great importance for national economies as well (Özden 2015; Cetin 2013a, b, 2015a, b; Kaya et al. 2018; Cetin et al. 2012a, b; Cetin 2016, 2017; Varol et al. 2019; Cetin et al. 2018).

Fly ash (FA) is a byproduct of thermal power plants in which coal is burned and is produced by means of electro filters before cooling during the melting of inorganic substances in the furnace and expulsion from the chimneys (Türker et al. 2009). Coal has two classes, F and C, according to the American Society for Testing Materials (ASTM) standard C618-17a (ASTM C618-17a, 2017), depending on the chemical composition, which is a result of the combustion type. F-class ashes are produced by burning anthracite or bituminous coal ($SiO_2 + Al_2O_3 + Fe_2O_3 \geq \%70$), and C-class ashes are produced by burning low-bituminous coal ($SiO_2 + Al_2O_3 + Fe_2O_3 \geq \%50$). C-class ash, also called high-calcareous fly ash, has a CaO content greater than 10% and has partial binding features in addition to low pozzolanic characteristics (Ghosh and Singh 2013; Tan et al. 1997; Pogrzeba et al. 2015; Xenidis et al. 2002; Türker et al. 2009).

Blast furnace slag (BFS) is defined as a byproduct that is formed when metals or metal-containing ores are melted and is a complex of oxides and silicates that are lighter than metal and accumulate on the surface due to density differences (Unal et al. 2014).

BFS is widely used as a binding material in concrete or cement to obtain environmental and economic benefits as well as to provide high durability. Slag is the result of metallurgical processes such as the production of metals or purification of pure metals. BFS, which is produced as a result of iron ore production in blast furnaces, results from the use of 12 lime-based inorganic ions to remove impurities from the solidified metals. This slag, which is formed as a liquid layer floating above the liquid iron at a temperature of 1300–1600 °C, enters the furnace with iron ore, coke, and limestone (Öz 2017). FA and BFS, which are the subjects of this study, are environmental wastes that occur in significant amounts in Turkey and cannot be reused to obtain economic benefits. The usefulness of these wastes as additives in cement is very important in terms of minimizing environmental hazards and contributing economically.

Since radioactivity harms human health, numerous studies have been carried out in recent years (Binici et al. 2012a). Radiation beams decrease in intensity when passed through a substance. This reduction depends on the thickness of the material, the elements contained therein and the concentrations of elements in the substance. To absorb X- and γ-rays, materials made of heavy elements are used. Lead is the most important radiation shielding substance used in industry. For this purpose, walls and doors in places working with radiation are covered with lead plates. Lead is a heavy element because of its specific gravity. Therefore, as an alternative to lead, it is important to identify other materials with high radiation absorption characteristics for use in industry (Sevinc 2011). The usage of radiation shielding basic materials in construction is important in terms of creating healthier living environments and allowing construction to proceed without any extra work or load (Sevinc 2011).

In this study, the reusability of FA and BFS from industrial waste materials at a construction site was investigated. These two waste materials were added to Portland cement together and separately in different amounts, and the radiation absorption properties of the mixtures were investigated, as well as their physical and mechanical properties under the influence of high temperature. The results reveal the possibility of economically using these environmentally harmful wastes as well as how they affect the quality and radiation permeability of cement produced by using these wastes as additives.

Materials and methods

Materials

Cement In this study, PC 42.5R (CEM I) cement was used. The chemical and physical properties of the cement are given in Table 1.

Fly ash and blast furnace slag FA and BFS were used as additives in the experimental study. The FA and BFS used in the experiments were milled to be finer than the Portland cement. The chemical composition and physical properties of the FA and BFS are given in Table 2.

Table 1 Chemical and physical properties of PC 42.5 cement

Oxide	Value	Property	Value
SiO_2	19.86	Specific surface area, cm^2/g	3440
Al_2O_3	4.95	Volume expansion, mm	1.5
Fe_2O_3	3.15	Normal water content (%)	27.9
CaO	63.50	Initial setting time, min	180
MgO	1.67	Final setting time, min	235
SO_3	3.93	Density, g/cm^3	3.09
Na_2O	0.16	Fraction retained at 40 μm (%)	13.4
K_2O	0.76	Fraction retained at 90 μm (%)	0.9
Total	97.98		

Methods

Production of cements and cement experiments Cement was produced by using FA, BFS, and FABFS via the substitution method at 5%, 10%, 15%, and 20% ratios. The mortars were produced in 40 × 40 × 160 mm dimensions (ASTM 2002). The amount of water required in each mixture was determined by flow table tests according to the flow diameter specified in ASTM standards C230, C109, and C1437 (Bayraktar et al. 2019c). The produced samples were stored at 20 ± 2 °C at a relative humidity of 95%.

Production of cement mortars and mortar experiments The chemical composition and physical properties of the PC 42.5, FA and FABFS that were used in the production of PC 42.5, FA, BFS, and FABFS blended cements were determined. The experimental methods were performed by using triple steel mortar molds with dimensions of 40 × 40 × 160 mm (Bayraktar et al. 2019c). Three types of mortar samples (FA, BFS, and FABFS) prepared with CEN standard sand were subjected to flexional and compressive strength tests at two different ages (28 and 90 days). Mortar samples were produced in the form of mortar prisms with dimensions of 40 × 40 × 160 mm. Samples were removed from the molds after 24 h and kept in a laboratory with 95% relative humidity at 20 ± 2 °C until the experiments on the 28th and 90th days. The mixture ratios used in the experiments were determined by calculations considering the flow rates. The mortar sample with cement binding was named PC 42.5; the mortar samples bonded with cement and FA at 5, 10, 15, and 20% ratios were named FA5, FA10, FA15, and FA20, respectively; the mortar samples bonded with cement and BFS at 5, 10, 15, and 20% ratios were named BFS5, BFS10, BFS15, and BFS20, respectively; the mortar samples bonded with cement and a mixture of FA and BFS at 5, 10, 15, and 20% ratios were named FABFS5, FABFS10, FABFS15, and FABFS20, respectively.

Table 2 Chemical composition and physical properties of FA and BFS

Oxide (%)	FA	BFS	Physical property	FA	BFS
SiO_2	53.11	39.03	Density, g/cm^3	2.05	2.90
Al_2O_3	18.49	13.48	Fraction retained at 40 μm (%)	35	12
Fe_2O_3	11.38	0.90	Fraction retained at 90 μm (%)	7	0.6
CaO	5.75	37.14	Specific surface area (Blaine) (m^2/kg)	4800	3750
MgO	4.87	5.45			
SO_3	1.16	0.08			
K_2O	1.87	1.15			
Na_2O	0.91	0.63			
K.K.	1.10	–			
Total	98.64	97.86			

High-temperature treatment The application of high temperature was carried out in accordance with the requirements of standard BS EN 13501-1 (BS EN 13501-1 2007). After curing periods of 28 and 90 days, the mortar samples were stored in an oven (105 ± 5 °C) for 24 h before exposure to high temperature. The mortar samples, which were dried in the oven, were placed in a high-temperature oven to determine the effect of high temperature. During the heat treatment phase, the samples were heated at 6 °C/min in the high-temperature oven at 150, 300, 700 and 900 °C for 2 h (Bayraktar et al. 2019c). Reference mortar samples at 20 °C were not exposed to high temperature.

Cooling process The samples that were kept at 150, 300, 700, and 900 °C for 2 h for high-temperature treatment were cooled in air (20 ± 2 °C in the laboratory). Flexural strength and compressive strength tests were performed on the mortar samples after the cooling process. The air-cooled mortar samples were kept in the laboratory for 30–180 min, depending on the cooling speed, until reaching a temperature of 20 °C.

Compressive strength and flexural strength experiments The compressive strength and flexural strength values were determined by subjecting 3 samples representing each high-temperature exposure group to compressive strength and flexural strength tests 1 day after beginning cooling (Bayraktar et al. 2019c; Ünal and Uygunoglu 2004).

Determination of linear absorption coefficients The radiation permeability of the samples was tested at 59.6 keV, 26 keV, 17.3 keV, and 5.9 keV energy levels. In this study, a Si (Li) solid-state detector with a resolution of 155 keV at 5.9 keV was used. When a radiation beam passes through an absorber, its intensity decreases. Fe-55 and Am-241 radioisotope sources were used as radiation sources in this study. The sample thicknesses were 3 cm. A Si (Li) solid-state detector with 155 keV resolution was used at 59.60 keV. The count spectra were evaluated with the help of an S100 card. The radioactive permeability of the samples was determined by calculating the percentage of the passed and absorbed radioactive rays at different energies (Binici et al. 2015).

The radioactive permeability was calculated from the following correlation (Eq. 1):

$$\mu = \ln\left(Io/Ix\right)/(X) \qquad (1)$$

whereIo is the intensity of the measured rays in the absence of a sample;Ix is the intensity of rays passing through a sample of thickness X;X is the sample thickness.

Experimental findings and discussion

Physical properties of produced cement

The produced cement samples were tested for density, Blaine area, initial and final setting time, and fineness (% retained at 40 μm and % retained at 90 μm), and the results are given in Table 3.

The lowest Blaine values of the produced samples were obtained for BFS5, and the highest values were found in FABFS20. The lowest density was found in FABFS20, and the highest density was that of BFS5. The initial and final setting times of the produced cements fell within specified limits (Bayraktar et al. 2019c).

Flexural strength of FA and BFS mixed mortars

Table 4 shows the flexural strength test results for the FA, BFS, and FABFS cement mortar prisms on the 28th and 90th days. The results were evaluated in accordance with the substitution rate of FA and BFS in the cement and mixing water, and the mechanical properties of the cement mortar were evaluated with respect to high-temperature treatment.

Table 4 indicates that the flexural strengths of 28-day-old FA5, FA10, FABFS10, FABFS15, and FABFS20 were greater than those of additive-free PC 42.5 cement at 20 °C (ref.) and 150 °C; the flexural strengths of FA15, FA20, BFS5, BFS10, and BFS15 were close to those of additive-free PC 42.5 cement at 20 °C (ref.) and 150 °C.

The flexural strengths of 90-day-old FA5, FA10, FA15, BFS5, FABFS5, FABFS10, FABFS15, and FABFS20 were greater than those of additive-free PC 42.5 cement at 20 °C (ref.) and 150 °C; the flexural strength of the FA20 sample was close to that of additive-free PC 42.5 cement at 20 °C (ref.) and 150 °C.

There was a difference between the 28th and 90th days according to the type of blended mortar sample: the flexural strength decreased with temperature from 300–900 °C. A comparison of the produced mortar samples after 28 and 90 days of air cooling revealed that the highest and lowest flexural strength values were obtained at 150 and 900 °C, respectively.

Compressive strength of FA and BFS blended mortars

The compressive strength test results of the 28- and 90-day-old FA, BFS, and FABFS blended cement mortar prisms are given in Table 5. The substitution rates of FA and BFS in cement were evaluated in accordance with the mixing water, and the effect of cement mortar on the mechanical properties at high temperature was investigated.

Table 5 shows that the compressive strengths of 28-day-old BFS20 samples were greater than the values obtained for pure PC 42.5 cement at 20 (ref.), 150, 300, and 700 °C; the compressive strengths of FA5, BFS5, BFS10, BFS15, FABFS5, and FABFS10 were greater than the values obtained for pure PC 42.5 cement at 20 (ref.), 150, 300, 700, and 900 °C; the compressive strengths of FA10, FABFS15, and FABFS20 were close to the values obtained for pure PC 42.5 cement at 20 (ref.), 150, and 300 °C.

The compressive strengths of 90-day-old FA20, BFS5, BFS10, BFS15, BFS20, FABFS5, FABFS10,

Table 3 The physical properties of various cement types

Cement type	Density (g/cm^3)	Blaine area (cm^2/g)	Initial setting time (min)	Final setting time (min)	Fraction retained at 40 μm (%)	Fraction retained at 90 μm (%)
PC 42.5	3.09	3440	190	225	13.4	0.9
FABFS5	3.01	3750	220	240	11.5	1
FABFS10	2.97	3792	230	250	11.8	1.1
FABFS15	2.93	3833	235	255	12.1	1.2
FABFS20	2.90	3875	245	265	12.3	1.3
FA5	3.04	3660	175	210	14.2	1.2
FA10	3.00	3680	195	230	14.9	1.5
FA15	2.95	3690	215	280	15.6	1.8
FA20	2.91	3710	235	340	16.3	2.2
BFS5	3.08	3475	205	240	10.7	1
BFS10	3.06	3490	215	250	11.5	1.1
BFS15	3.04	3506	220	255	12.4	1.1
BFS20	3.02	3521	230	265	13.2	1.2

FABFS15, and FABFS20 were greater than the values obtained for pure PC 42.5 cement at 20 (ref.), 150, 300, 700, and 900 °C; the compressive strengths of FA5, FA10, and FA15 were quite close to the values obtained for pure PC 42.5 cement at 20 (ref.), 150, 300, 700, and 900 °C.

Comparison of the produced mortar samples after 28 and 90 days of air cooling revealed the highest and lowest resistances for the mortar samples at 150 and 900 °C, respectively.

Determination of linear absorption coefficients

The radiation permeability of the samples at 59.6 keV, 26 keV, 17.3 keV, and 5.9 keV was examined; the samples absorbed all radiation at 17.3 keV and 5.9

Table 4 Flexural strength of mortar samples

Flexural strength (MPa)

Conditions	Day	28					90				
	Cooling process	20 (ref.)	In air				20 (ref.)	In air			
	High-temperature treatment (°C)		150	300	700	900		150	300	700	900
Mortar type	PC 42.5	8.2	8.4	7.7	4.9	2.9	9.1	9.3	9	6.6	3.5
	FA5	8.3	9.1	8.5	5.1	3	9.4	10.1	10	6.9	3.6
	FA10	8.4	8.9	8.1	5.1	3	9.5	10.2	9.2	5.3	2.9
	FA15	8.2	8.5	7.9	4.6	2.6	9.2	9.6	8.8	4.6	2.3
	FA20	8	8.6	8	4.4	2.3	8.9	9.7	8.9	4.3	1.9
	BFS5	8.3	8.3	7.4	4.8	2	9.2	9.4	8.3	6.8	1.7
	BFS10	8.4	8.2	7.3	4.4	1.6	9.3	8.4	7.3	5.4	0.8
	BFS15	8.6	8.2	7.3	5.9	1.8	9.5	8.7	7.2	5.4	0.4
	BFS20	8.8	7.8	6.3	4.9	2	9.6	8.5	7.3	6.4	0.7
	FABFS5	9.4	9.8	9	6	3.5	10.8	11.7	11.1	8.8	4.6
	FABFS10	9.7	9.9	8.9	5.9	3.4	11.2	11.1	10	7.1	1.1
	FABFS15	10	9.9	9.1	6.8	3.7	11.6	11.4	10.2	7.2	3.6
	FABFS20	10.3	10.1	9	7.5	5	11.9	11.7	10.7	8	3.9

Table 5 Compressive strength of mortar samples

Compressive strength (MPa)

Conditions	Day	28					90				
	High temp. app. (°C)	20 (ref.)	150	300	700	900	20 (ref.)	150	300	700	900
Mortar type	PC 42.5	46.2	48.2	44.6	28.4	25.6	58.5	60.3	55.3	36.2	31.2
	FA5	47.8	49.1	45.6	29.4	26.5	56.8	53.5	51.3	35.3	32.2
	FA10	43.4	45.2	41.2	25.3	22.1	57.4	54.6	53.5	37.2	34.3
	FA15	42.2	37.2	34.3	16.6	13.5	58.7	59.6	58.2	42.5	39.1
	FA20	41.9	34.1	31.5	13.6	10.6	60.3	61.3	60.5	44.1	41.3
	BFS5	55.1	57.6	54.4	40.6	38.8	75.4	75.8	71.9	56.8	53.5
	BFS10	51.5	54.3	51.6	37.6	35.2	68.4	71.7	68.2	53.9	52.1
	BFS15	50.6	52.8	49.1	34.5	32.1	66.8	68.9	65.7	51.8	48.9
	BFS20	49.7	51.9	47.3	31.6	23.5	65.3	67.9	63.8	48.7	42.1
	FABFS5	50.8	53.7	49.9	35.2	32.8	66.7	64.6	61.8	46.7	42.8
	FABFS10	47.5	49.8	46.8	31.8	28.7	62.9	63.1	61.1	45.8	43.1
	FABFS15	46.2	44.7	41.9	25.7	23.1	62.4	64.2	61.7	47.1	44.2
	FABFS20	45.7	43.1	39.2	21.2	17.3	62.8	64.5	62.2	46.3	40.6

keV, so the I values were zero at these energy levels. The values obtained at 26 keV and 59.6 keV are given in Table 6.

The linear absorption coefficient indicates the radiation absorption value of a material. The higher the μ value is, the higher the radiation absorption capacity. Table 6 shows that the FABFS samples absorbed the most radiation at 26 keV. The FABFS samples transmitted six per thousand of 26 keV energy rays. The BFS sample transmitted the most radiation, 2.2% of the rays. These results indicate that the FABFS sample can be easily used as a radiation-absorbing material in places with 26 keV energy. The BFS sample transmitted 45% of the 59.6 keV rays, but 39% of the rays passed the FA sample. Here, the FABFS sample absorbed the most radiation at 59.6 keV, but this absorption ratio of these mortars at this energy level is not sufficient. At this level of energy, it would be necessary to increase the thickness of the FABFS sample to be able to use this material in industry. The FABFS sample can be used as a radiation-absorbing material. Those who use lead vests in medicine and work with radiation can reduce the effect of radiation by using this material. The proposed material can also be used as a wall covering in medical buildings. Thus, the negative effects of high-energy radiation can be reduced (Binici et al. 2012b).

Results and discussion

The flexural strength and compressive strength at all temperatures above 150 °C decreased on days 28 and 90. This result may have occurred because the mineral additives used in this research reduce the number of pores in mortar samples. In addition, the amount of $Ca(OH)_2$ decreases in the system due to the pozzolanic reaction occurring between the reactive silica (SiO_2) in the mineral additives and the $Ca(OH)_2$ in the cement (Demirel and Kelestemur 2011). Mixtures containing a certain proportion of mineral additives substituted in the cement contain less calcium hydroxide than pure PC cement, which may also be the reason for the increase in strength at temperatures up to 150 °C.

Today, cement is the most widely used binding material in the construction sector. The energy involved in cement use has also revealed economic and environmental problems. Approximately 7% of the total CO_2 emissions in the world are caused by cement production. Therefore, producing alternative cements for portland cement is a current research topic (Binici et al. 2012a). Since the additives used to produce cement are industrial wastes that damage the environment, it is important to avoid the environmental pollution caused by the use of these materials in mortar and to reduce the costs of the samples produced. Additive cements are important in

Table 6 Intensity values for samples at 26 keV and 59.6 keV energy

Energy	Sample name	*t* (cm)	*Io*	*I*	*I*/*I*o	μ (cm^{-1})
26 keV	FABFS	3	3956	26	0.006	1.705
	FA	3	3956	73	0.018	1.339
	BFS	3	3956	88	0.022	1.272
59.6 keV	FABFS	3	139478	41490	0.297	0.509
	FA	3	139478	55717	0.399	0.306
	BFS	3	139478	63824	0.457	0.261

terms of sustainable concrete technology, in addition to providing environmental gains.

The mortar experiments indicated that the density, flexural strength, and compressive strength of the additive mortar samples at all ages decreased in proportion to the amount of FA and BFS. The initial and final setting times of the FA5 and FA10 blended mortar samples were lower than those of the BFS5 and BFS10 blended mortar samples; however, the initial and final setting times of FA20 were higher than those of BFS20 among the 28-day samples. The mortar samples blended with FA demonstrated strengths similar to those of the control mortar samples, while the BFS blended mortars and FABFS5 and FABFS10, which are double additive samples, presented higher compressive strengths than the FA-blended mortar samples.

On the 90th day, the samples with FA as an additive had compressive strengths close to that of the PC 42.5 control cement at all temperatures; the FA20 sample gave a greater strength than the control cement; all samples with BFS and double additives gave higher strengths than the control cement; and all the samples with BFS as an additive gave higher strengths than the samples with FA as an additive. From these data, it was concluded that BFS was more effective than FA in terms of the strength of advanced-age cement due to its pozzolanic activity.

On the 28th day, at all temperatures, the compressive strengths of the FABFS5 and FABFS10 blended samples were higher than those of samples blended with FA; on the 90th day, all the samples blended with FABFS gave higher compressive strengths at all temperatures than the FA-blended mortar samples.

The detrimental effect of high temperature was more pronounced on bending strength than compressive strength. Comparing the reference cement with the FA- and BFS-blended cements indicated that the most suitable additive ratio is 20% in terms of strength, physical properties, and usability. The sample with the highest linear absorption coefficient was the mortar sample produced with FABFS as an additive. In other words, the sample with the highest linear absorption coefficient was that with the least radioactive permeability.

In the microstructures of sections taken from mortar samples treated at high temperature, aggregate distribution, crack development, and pore structure could not be distinguished well up to 300 °C, but at higher temperatures, the cracks between aggregate grains of binder grew. The increase in flexural strength and compressive strength of the mortar samples from 100 to 300 °C and the water vapor formed at high temperature caused high pressures in the blended mortar samples (Bayraktar 2016). This process creates internal balance.

The strength increase up to 300 °C was caused by the gel layers in the matrix shifting closer to each other as a result of the evaporation of free water, increasing the attraction due to the greater van der Waals forces (Khoury 1992; Hossain 2006). This situation was especially observed in the 90-day-old samples. According to previous studies, calcium hydroxide and calcium silicates are completely decomposed at 500 °C and 900 °C, respectively (Bayraktar 2016). In the experimental study herein, some experimental results for samples at 700 and 900 °C indicated low strengths.

According to the experimental results, it was determined that concrete with high strength can be produced by using BFS and FA in combination, especially at advanced ages. Microstructure investigations demonstrated that the internal structure of the 90-day-old blended cements became more filled with CSH gels resulting from the pozzolanic reaction. As a result of cement hydration, $Ca(OH)_2$, formed as a hydration product, starts to react with pozzolans. The result is an increase in the amount of CSH gels, which give strength to concrete. In this way, the increase in compressive strength on the 28th and 90th days can be attributed to the amount of pozzolan.

The most important parameter for the use of BFS in cement and concrete is the amount of glassy phase it contains. The chemical composition is also important. For example, the amount of $CaO+SiO_2+MgO$ is expected to be at least 67% (Tokyay 2013). The total $CaO+SiO_2+MgO$ content of the BFS used in this study was 81.62% (Table 2). According to ASTM C 618, the total amount of $SiO_2+Al_2O_3+Fe_2O_3$ in FA is expected to be at least 70% by weight (Tokyay 2013). The sum of $SiO_2+Al_2O_3+Fe_2O_3$ in the FA used here was 82.98%, and the two pozzolans were above the boundary conditions (Table 2). Therefore, the FA and BFS used in this study are suitable for use in cement and concrete.

Studies on the use of different substitutes in cement are very important in terms of both waste disposal and cost reduction. Therefore, many studies have been carried out on this subject. Tang and Lo (2009) concluded that BFS additives perform better in terms of mechanical properties than other pozzolan-added concretes or additive-free concretes at high temperature. This study demonstrated that the BFS additive contributed positively to durability and strength. The use of mineral additives as binary mixtures solved the deficiencies caused by the use of mineral additives alone. In other words, the mineral additives in the FABFS mixture complemented each other, allowing the material properties to be closer to those of the reference sample and resulting in a more homogenous material at an early age while reducing the amount of cavities and ettringites. Another important point is that the contributions to the environment and economy achieved by the use of binary mixtures can provide significant benefits.

Kabeer and Vyas (2018) used marble dust (MD), a waste product formed during the cutting and shaping of marble blocks, to replace traditional river sand in cement mortars. The results of their study indicated that mortars blended with river sand and MD at a 20% ratio can be used for masonry and processing purposes. Khodabakhshian et al. (2018) added silica fume (0%, 2.5%, 5%, and 10%) and waste MD (0%, 5%, 10%, and 20%) to portland cement at different proportions and found that the durability and strength of the concrete containing waste MD tended to decrease at proportions over 10% but satisfactory results were obtained below this level. Yildiz et al. (2017) investigated the mechanical and physical properties of waste MD- and glass fiber-added cement mortars exposed to sulfate attack and concluded that the use of up to 40% (by volume) MD in glass fiber-reinforced mortar samples to increase tensile strength could provide positive gains in terms of both economy and sulfate resistance.

Kara and Yazicioglu (2016) determined that as the carbonation depth increased in concrete samples produced by substituting different amounts of MD waste and 10% silica fume, the ultrasound velocity increased, the capillarity coefficient decreased, the amount of wear decreased and the compressive strength increased.

Açikgenc et al. (2013) stated that, instead of cement, Elaziğ region limestone powder and waste brick powder could be used as mineral additives in mortar at low substitution rates by the substitution method. Nežerka et al. (2014) studied nine different paste sets with metakaolin and brick dust and showed that metakaolin exhibited a much stronger pozzolanic activity than brick dust and did not necessarily increase the mechanical properties of pastes with the addition of pozzolan.

Kaya and Yazicioglu (2015) investigated the effect of high temperature on the mechanical and physical properties of calcined mortar and concluded that the lowest resistance losses before and after high-temperature exposure were obtained from the reference sample at 500 °C and from 10% bentonite-added samples at 750 and 1000 °C. Gökcer et al. (2013) added waste MD to mortar samples reinforced with different amounts of glass fiber by displacing the filling material at 10%, 20%, and 30% by weight. They stated that the use of waste MD in the glass fiber-blended mortar samples yielded a denser structure and thus caused less strength loss in high-temperature mortar samples.

Öz (2017) stated in his study that mineral additives such as waste glass dust and BFS improve the basic mechanical properties, such as compressive strength and flexural strength, of self-compacting mortars, and that while the compressive strength of the produced mortars varied between 26.54 and 80.4 MPa, the flexural strength of the samples ranged from 5.8 to 10.2 MPa. He concluded that generally lower values than those of the control mortar were obtained from BFS15 and subsequent mortar samples. In his study, the compressive strength of the produced mortars ranged from 10.6 to 75.4 MPa, while the flexural strength varied between 0.4 and 11.9 MPa. This change shows that the maximum values were similar, but the difference in the minimum values was due to the high-temperature effect. The values obtained for FABFS20 on the 28th day were lower than but close to those for the control mortar. Therefore, he concluded that the most appropriate additive rate was 20%.

Binici et al. (2012c) concluded in their study that light construction materials produced from cotton waste, FA and adhesive resin could be used for heat and sound insulation and that the radioactive permeability of barite lightweight building materials was low. Binici et al. (2012d) stated in another study that the sample with the highest linear absorption coefficient was a geopolymer obtained from BFS and that this material with low radioactive permeability could be used in structures exposed to radiation effects. Binici et al. (2015) reported that the use of egg shells as an additive to increase the radiation absorption properties of mortars reduces the radioactive permeability and therefore can be used in structures exposed to radiation effects. Ling et al. (2013) studied the X-ray radiation protection properties of cement mortars prepared with six different aggregate types and found that mortars prepared with recycled CRT funnels with barite or lead loaded with glass had increased radiation protection ability as well as an increased mortar density. In particular, they concluded that barite mortar could be used as plaster.

New trends in environmental regulations seek to make use of industrial byproduct wastes such as BFS and FA as partial substitutes in the production of mortar and concrete instead of cement and aggregates (Saridemir 2016). By making use of these wastes as raw materials, environmental pollution can be prevented, and the wastes can be supplied to the economy as construction materials (Bayraktar 2016, Bayraktar et al. 2018; Bayraktar et al. 2019a, b; Merkit et al. 2018; Yilmaz 2014; Akyildiz et al. 2017; Köse and Akyildiz 2017; Subasi et al. 2017; Binici et al. 2012c). By using these wastes, raw materials must be obtained by using the wastes alone or mixing them with other materials to produce new materials that are appropriate according to the standards in use (Bilgin 2010). CO_2 emissions can be minimized by the use of industrial wastes such as FA, BFS, and silica fume in cement-based systems (such as plaster, mortar, and concrete), reducing the need for natural resources and energy (Tangüler et al. 2015).

Fire is a phenomenon that occurs when solid, liquid, or gaseous substances burn out of control. Uncontrolled fire is often seen as a catastrophe that causes significant loss of life and property. This situation has revealed the importance of active measures in fire protection (Baradan et al. 2010). It has been observed that concrete is more resistant to high temperatures and fire than many building materials. Concrete is defined as a material with high fire resistance because it does not cause significant damage for a certain period of time and does not produce toxic fumes (Neville 2000). However, this durability is valid only for certain times and temperatures (Baradan et al. 2010). For example, in normal-strength concrete produced with silica-based aggregates, the strength loss at 600 °C is approximately 50% (Neville 2000). Events causing a loss in compressive strength at high temperatures have been explained by a thermal mismatch between the cement paste and aggregate, connections in the aggregate cement interface, the pressure of evaporating water at high temperature, and changes in the chemical structure of the cement paste and aggregate (Cülfik 2001). According to the above studies, a number of differences and advantages have been observed (Table 7).

Suggestions

This study has demonstrated that industrial wastes such as FA and BFS can be used in cement production at different rates both separately and together. Because these materials are waste materials, their use in mortar is important to prevent the environmental pollution caused by these materials and to reduce the costs of

Table 7 Differences and advantages according to the above studies

Differences	
Materials are waste materials	Prevents environmental pollution
Economic	Reduces the costs of the samples produced
	The quality of concrete changes depending on the proportion of materials used
Suitability and sustainability	FA5 and FA10 cements are more suitable for concrete production
Strength	Suitable additive for fire resistance
Temperature	Suitable
Physical and mechanical compatibility	Suitable additive for fire resistance

the samples produced. At this point, it is important to know how the quality of concrete changes depending on the proportion of materials used. According to the results obtained in this study, the use of FA5 and FA10 cements is more suitable for concrete production conditions where early strength is important and weather conditions are cold.

The compressive strength of 28-day-old samples with FA as an additive was close to the control mortar strength at all temperatures; the samples with BFS as an additive and the binary mixtures FABFS5 and FABFS10 had higher compressive strengths than the control mortar; and the samples with BFS as an additive and binary additives of FABFS5 and FABFS10 had higher strengths than the samples with FA as an additive.

At all temperatures, on the 28th day, the compressive strengths of the FABFS5 and FABFS10 blended samples were higher than those of samples blended with FA; on the 90th day, all the samples blended with FABFS had higher compressive strengths at all temperatures than the blended FA mortar samples. In consideration of these results, it will be beneficial to determine the mixture ratios in cement production.

On the 90th day, at all temperatures, the compressive strength of the samples with FA as an additive was close to the control mortar strength; the samples with FA20 had higher strength than the control mortar; the samples with BFS as an additive and all the binary blended samples had higher strengths than the control mortar; and all the samples with BFS as an additive and the binary blended samples had higher strengths than the samples with FA as an additive.

Therefore, the most suitable additive for fire resistance is BFS, but FABFS is the most suitable additive when considering not only fire but also multidimensional (economic and environmental) aspects. The cement production results in this study allow the selection of additive rates that do not make significant concessions in cases where exposure to high temperature in concrete design may occur. For example, the compressive strengths of FABFS15 and FABFS20 after 28 days were quite close to that of the PC 42.5 mortar. The 90th day compressive strengths of the FA and BFS additive samples were close to or higher than that of the PC 42.5 mortar, and all the binary mixtures had higher strengths than the PC 42.5 mortar, proving that by using these two industrial wastes in cement production, it is possible to produce more environmentally friendly and economic cement.

High temperature is an important factor in sustainability and causes significant losses in concrete design and mechanics. In concrete structures, high-temperature exposure situations such as fire, explosion, and combustion must always be taken into consideration. Cement mortars would be less damaged less by high temperatures when using FA and BFS as substitutes. Higher temperature ranges can be applied in further studies. Thus, potential accidents can be minimized in structures that may be exposed to high temperatures.

Today, persistence is an important parameter in addition to strength in the production of sustainable structures. It could be beneficial to examine the additive mortars considered in this study (with regard to physical and mechanical compatibility) in terms of persistence in further studies. The positive effects of additive cements on concrete permanence will enable the resulting structures to serve without problems for years.

According to the experimental results, concrete with high strength can be produced by using BFS and FA in combination, especially at advanced ages. In addition to the pozzolan features of the slag, thanks to the microfiller features, the amount of fine aggregates can be reduced, and the thinness of the pozzolan is estimated to be increased.

These results indicate that FABFS samples can be easily used as radiation-absorbing materials in places with 26 keV energy. While the BFS sample transmitted 45% of 59.6 keV rays, 39% of the rays passed the FA sample. Here, the FABFS sample absorbed the most radiation at 59.6 keV, but the absorption ratios of these mortars at this energy level are not sufficient. At this level of energy, it is necessary to increase the thickness of the FABFS sample to be able to use the material in industry. The FABFS sample can be used as a radiation-absorbing material. Those who use lead vests in medicine and work with radiation can reduce the effect of radiation by using this material. FABFS can also be used as a wall covering in medical buildings. Thus, the negative effects of high-energy radiation can be reduced.

Environmental factors should be considered in sustainable concrete design. By reducing the carbon dioxide (CO_2) and greenhouse gasses emitted in cement production, it is possible to prevent the destruction of nature and environmental pollution to some extent. Today, from the perspective of sustainable architecture, the technical and economic potential of the cement production process should be reconsidered in order to provide environmental benefits to national economies and further benefits to the construction industry. Thus, environmental, economic and, most importantly, significant human life benefits can be provided.

References

Açikgenc, M., Karatas, M., & Ulucan, Z. C. (2013). The effect of the waste brick and limestone dust of the Elazig region on the engineering properties of the self-contained mortar. PamFAkale University. *Journal of Engineering Sciences, 19*(6), 249–255.

Akyildiz, A., Köse, E. T., & Yildiz, A. (2017). Compressive strength and heavy metal leaching of concrete containing medical waste incineration ash. *Construction and Building Materials, 138*, 326–332.

American Society For Testing And Materials. (2002). *C109/C109M-02 standard test method for compressive strength of hydraulic cement mortars*. American: Society for Testing and Materials International.

American Society for Testing and Materials. (2017). *C618-17a Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete*. American: Society for Testing and Materials International.

Baradan, B., Yazici, H., & Ün, H. (2010). *Persistence in concrete and concrete structures (durability), Turkey Ready Mixed Concrete Association*. Istanbul: Publications.

Bayraktar, O. Y. (2016). Statistical comparison of mechanical behavior at the time of accident in the mortars produced with pozzolanic additives, Gazi University, Institute of Science and Technology, Ph.D. Thesis, Ankara.

Bayraktar, O. Y., Saglam-Citoglu, G., Caglar, H., Caglar, A., Arslan, M., & Cetin, M. (2018). The mechanical properties of the different cooling requirements of high-temperature plaster. *Fresenius Environmental Bulletin, 27*(8), 5399–5409.

Bayraktar, O. Y., Saglam-Citoglu, G., & Abo Aisha, A. E. S. (2019a). The use of scrap tires in the construction sector. *International Journal of Trend in Research and Development, 6*(1), 253–256.

Bayraktar, O. Y., Saglam-Citoglu, G., & Abo Aisha, A. E. S. (2019b). Performance research of lime based mortars. *International Journal of Trend in Research and Development, 6*(1), 257–259.

Bayraktar, O. Y., Saglam-Citoglu, G., Belgin, C. M., & Cetin, M. (2019c). Investigation of the mechanical properties of marble dust and silica fume substituted portland cement samples under high temperature effect. *Fresenius Environmental Bulletin, 28*(5), 3865–3875.

Bilgin, N. (2010). Use of marble powder wastes in the production of building materials. Yildiz Technical University, Institute of Science and Technology, Master Thesis, Istanbul.

Binici, H., Gemci, R., Küçükönder, A., & Solak, H. H. (2012a). Thermal conductivity, sound insulation and radiation transmission of cotton waste, fly ash and barite reinforced chipboards. *Electronic Journal of Construction Technologies, 8*(1), 16–25.

Binici, H., Gemci, R., & Kücükönder, A. (2012b). Investigating the sound insulation, thermal conductivity and radioactivity of chipboards produced with cotton waste, fly ash and barite. *Construction and Building Materials, 30*, 826–832.

Binici, H., Sevinc, A. H., & Eken, M. (2012c). Production of insulation material with sunflower sticks and textile wastes. *Kahramanmaras Sutcu Imam. Journal of Engineering Sciences, 15*, 1–5.

Binici, H., Eken, M., & Aksogan, O. (2012d). Physical, mechanical and radiation permeability properties of slag, fly ash, silica sand and pumice based geopolymers. *Electronic Journal of ConstructionTechnologies, 8*(2), 12–25.

Binici, H., Aksogan, O., Sevinc, A. H., & Cinpolat, E. (2015). Mechanical and radioactivity shielding performances of mortars made with cement, sand and egg shells. *Construction and Building Materials, 93*, 1145–1150.

British Standards Institution (2007). 13501-1 Fire classification of construction products and building elements. Classification Using Data from Reaction to Fire Tests.

Brooks, R., & Cetin, M. (2012). Application of construction demolition waste for improving performance of subgrade and subbase layers. *International Journal of Research and Revies in Applied Science, 12*(3), 375–381.

Cetin, M. (2013a) Landscape engineering, protecting soil, and runoff storm water. In: Advances in landscape architecture-environ-mental sciences. Chapter 27. InTech-Open Science-Open Minds, Online July 1st, 2013. ISBN 978-953-51-1167-2, 697-722.

Cetin, M. (2013b) Pavement design with porous asphalt. PhD Thesis. Temple University. Philadelphia

Cetin, M. (2015a) Using recycling materials for sustainable landscape planning. In: Environment and ecology at the beginning of 21st century. Chapter 55. ST. Kliment Ohridski University Press, Sofia, ISBN:978-954-07-3999-1, 783-788. 821p.

Cetin, M. (2015b). Consideration of permeable pavement in landscape architecture. *Journal of Environmental Protection and Ecology., 16*(1), 385–392.

Cetin, M. (2016). A change in the amount of CO2 at the center of the examination halls: case study of Turkey. *Studies on Ethno-Medicine., 10*(2), 146–155.

Cetin, M. (2017). Change in amount of chlorophyll in some interior ornamental plants. *Kastamonu University Journal of Engineering and Sciences., 3*(1), 11–19.

Cetin, M., Brooks, R., & Udo-Inyang, P. (2012a). An innovative design methodology of pavement design by limiting surface deflection. *International Journal of Research and Reviews in Applied Sciences., 13*(2), 607–610.

Cetin, M., Brooks, R., & Udo-Inyang, P. (2012b). A comparative study between the results of an innovative design methodology by limiting surface deflection and AASHTO design method. *International Journal of Research and Reviews in Applied Sciences, 13*(2), 27.

Cetin, M., Adiguzel, F., Kaya, O., & Sahap, A. (2018). Mapping of bioclimatic comfort for potential planning using GIS in Aydin. *Environment, Development and Sustainability, 20*(1), 361–375. https://doi.org/10.1007/s10668-016-9885-5.

Cülfik, M. S. (2001) Deterioration of bend between cement paste and aggregate at high temperatures. Boğaziçi University, Institute of Science and Technology, Ph.D. Thesis, Istanbul.

Demirel, B., & Kelestemur, O. (2011). High temperature pumice and silica fume additive to the mechanical and physical properties of curing age impact of concrete. *Electronic Journal of Construction Technology, 7*(1), 1–13.

Ghosh, R. K., & Singh, N. (2013). Adsorption-desorption of metolachlor and atrazine in Indian soils: effect of fly ash amendment. *Environmental Monitoring and Assessment, 185*(2), 1833–1845.

Gökcer, B., Yildiz, S., & Kelestemur, O. (2013). High temperature behavior of waste marble powder and glass fiber mortar samples Süleyman Demirel University. *International Technology Science, 5*(2), 42–55.

Hossain, K. M. A. (2006). High strength blended cement concrete incorporating volcanic ash: performance at high temperatures. *Cement and Concrete Composites, 28*(6), 535–545.

Kabeer, K. I. S. A., & Vyas, A. K. (2018). Utilization of marble powder as fine aggregate in mortar mixes. *Construction and Building Materials, 165*, 321–332.

Kara, C., & Yazicioglu, S. (2016). Effect of carbonation of marble dust and silica fume. Bitlis Eren University. *Journal of Science, 5*(2), 191–202.

Kaya, T., & Yazicioglu, S. (2015). Investigation of high temperature effect on the physical and mechanical properties of bentonite additive mortars with calcium calcium. Bitlis Eren University. *Journal of Science and Technology, 4*(2), 150–160.

Kaya, E., Agca, M., Adiguzel, F., & Cetin, M. (2018). Spatial data analysis with R programming for environment. *Human and Ecological Risk Assessment: An International Journal*. https://doi.org/10.1080/10807039.2018.1470896.

Khodabakhshian, A., Ghalehnovi, M., De Brito, J., & Shamsabadi, E. A. (2018). Durability performance of structural concrete containing silica fume and marble industry waste powder. *Construction and Building Materials., 165*, 321–333.

Khoury, G. A. (1992). Compressive strength of concrete at high temperatures: a reassessment. *Magazine of Concrete Research, 44*(161), 291–309.

Köse, E. T., & Akyildiz, A. (2017). Cement based solidification/stabilization of red mud: leaching properties of heavy metals. *PamFAkale University Journal of Engineering Sciences, 23*(6), 741–747.

Ling, T. C., Poon, C. S., Lam, W. S., Chan, T. P., & Fung, K. K. L. (2013). X-ray radiation shielding properties of cement mortars prepared with different types of aggregates. *Materials and Structures, 46*(7), 1133–1141.

Merkit, Z. Y., Ozarslan, C., Aydin, B., & Toplan, N. (2018). The effect of mechanical activation on CAS ceramics produced using zeolite and marble powder. *Sakarya University Journal of Science, 22*(2), 680–687.

Neville, A. M. (2000). *Properties of Concrete* (Fourth ed.). New York: Longman Scientific and Technical.

Nežerka, V., Slížková, Z., Tesárek, P., Plachý, T., Frankeová, D., & Petráňová, V. (2014). Comprehensive study on mechanical properties of limebased pastes with additions of metakaolin and brick dust. Cement and concrete research, 64, 17–29.

Öz, H. Ö. (2017). Fresh, Mechanical and Durability Properties of Self-Leveling Mortars Including Waste Glass Powder and Blast Furnace Slag. Kahramanmaraş Sütçü İmam University. *Journal of Engineering Sciences, 20*(4), 9–22.

Özden, Ö. (2015). The Importance of Recycling in Environment and Economy. http://toplumhekimligi.istanbul.edu.tr/wp content / uploads / 2015/11 / The importance of recycle-environment-and-economics-Assist. Prof.

Pogrzeba, M., Galimska-Stypa, R., Krzyżak, J., & Sas-Nowosielska, A. (2015). Sewage sludge and fly ash mixture as an alternative for decontaminating lead and zinc ore regions. *Environmental Monitoring and Assessment, 187*(1), 4120.

Saridemir, M. (2016). Resistance characteristics of different distributed diatomy mortars with alkali. *Ömer Halisdemir University Journal Of Engineering Sciences, 5*(2), 124–134.

Sevinc A. H. (2011). Blast furnace slag, pumice, barite and colemanite additive properties of mortars and concretes, Kahramanmaras Sutcu Imam University, Institute of Science, Master Thesis, Kahramanmaras.

Subasi, S., Öztürk, H., & Emiroğlu, M. (2017). Utilizing of waste ceramic powders as filler material in self-consolidating concrete. *Construction and Building Materials, 149*, 567–574.

Tan, L. C., Choa, V., & Tay, J. H. (1997). The influence of pH on mobility of heavy metals from municipal solid waste incinerator fly ash. *Environmental Monitoring and Assessment, 44*(1-3), 275–284.

Tang, W. C., & Lo, T. Y. (2009). Mechanical and fracture properties of normal-and high-strength concretes with fly ash after exposure to high temperatures. *Magazine of Concrete Research, 61*(5), 323–330.

Tangüler, M., Gürsel, P., & Meral, C. (2015). Life cycle analysis for fly ash concretes in Turkey. 9th National Concrete Congress, 431-441.

Tokyay, M. (2013). The role of FA, GBFS and SD in concrete: present knowledge. Concrete 2013 Ready-Mixed Concrete Congress, 21-23 February, 201-238.

Türker, P., Erdoğan, B., Katnaş, F., & Yeğinobali, A. (2009). *Classification and characteristics of fly ash in Turkey*. TCMB: Ankara.

Ünal, O., Uygunoglu, T. (2004). The evaluation of soma thermal power plant waste integrated culture in construction sector. Proceedings of the 14th Coal Congress of Turkey, Zonguldak.

Unal S., Yucel O., Kurt M., Gul S. (2014), Iron-steel slag from waste to product, Advanced technologies workshop, 255–267.

Varol, T., Ertuğrul, M., Özel, H. B., Emir, T., & Çetin, M. (2019). The effects of rill erosion on unpaved forest road. *Applied Ecology and Environmental Research, 17*(1), 825–839. https://doi.org/10.15666/aeer/1701_825839.

Xenidis, A., Mylona, E., & Paspaliaris, I. (2002). Potential use of lignite fly ash for the control of acid generation from sulphidic wastes. *Waste Management, 22*(6), 631–641.

Yiğiter M. (2014). Production of plaster material from industrial wastes with short staple fiber character. Hitit University, Master Thesis, Corum.

Yildiz, S., Aliser, B., & Kelestemur, O. (2017). Investigation of mechanical and physical properties of waste mortar powder and glass fiber reinforced cement mortars under sulphate effect, Firat University. *Science Journal., 29*(2), 23–31.

Yilmaz, M. (2012). Turkey's energy potential and the importance of renewable energy sources for electricity production. *Ankara University Journal of Environmental Studies, 4*(2), 33–54.

Yilmaz Y. (2014). The effects of using fly ash and blast furnace slag on concrete production and cost analysis, Namik Kemal University, Master Thesis, Tekirdağ.