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High temperature resistance of boron active belite cement mortars containing fly ash

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ABSTRACT

Boron allowing stability of reactive belite phase in clinker production enhances neutron shielding capability of cement. In the study, neutron attenuation factor of boron active belite cements at various fly ash introduction was theoretically revealed by comparing with an alternative low heat cement (portland composite cement). High temperature resistance of the cements with and without fly ash introduction was determined on standard mortar prisms at elevated temperatures up to 900 °C with regard to compressive strength and flexural strength. Neutron shielding performance of boron active belite cement was found almost 25 times higher than Portland composite cement. Fly ash introduction significantly reduced the neutron attenuation factor of boron active belite cement. High temperature resistance of boron active belite cement mortar was found lower than that of Portland composite cement mortar at 700 °C at later curing time. 10% fly ash introduction improved the high temperature performance of boron active belite cement mortar exposed to 900 °C. Residual compressive strength values of the mortars containing fly ash were between 16% and 28% after exposing 900 °C.

1. Introduction

Increment in nuclear applications with evolving technology enforce researchers to work on efficiently shielding various types of radiation derived from the applications used in many industrial fields. Unlike to gamma rays, fast neutrons can be slowed down by elastic collisions with moderator materials that are low atomic-number elements ($Z \leq 16$) such as commonly known hydrogen and boron (Mehta and Monteiro, 2006; NCRP, 1957). When compared to conventional concrete, with the 25–50% higher unit weight (Lo Monte and Gambarova, 2014) and almost 30% higher linear attenuation coefficient for gamma rays (Mostofinejad et al., 2012), heavyweight barite concrete has become a famous research topic in material and physical science (Gökçe et al., 2018a). Although the heavyweight concrete is known as satisfactory shielding material (Mehta and Monteiro, 2006), recent studies show that an optimization in shield design allow simultaneous shielding neutrons and gamma rays (El-Khayatt, 2011; Akkurt and El-Khayatt, 2013; Gökçe et al., 2018b). Thus, effective shielding materials for nuclear reactors can be achieved by mixing hydrogenous materials, heavy metal elements, and other neutron absorbers (El-Khayatt, 2011).

Heavyweight concrete is generally formed by heavy aggregate portion containing heavy elements such as barium and lead, and paste portion providing hydrogenous moderator materials against neutrons. Thus, enhancement in neutron shielding capability of the paste can improve the total neutron shielding capability of the concrete mixtures. It is well-known that boron-bearing materials present enhanced neutron shielding capability in such cement-based composites (Glinicki et al., 2018). However, Davraz (2015) reported that boron compound retards setting time and impairs strength of the cementitious products when used as an external admixture.

On the other hand, conventional portland cement presenting higher cost per ton causes more environmental damage than blended and low carbon cements (Berriel et al., 2018). The indispensable component for concrete production is produced in more than 150 countries, and is consumed worldwide in many fields (Shen et al., 2014). Recent studies have mainly focused on high volume fly ash cementitious systems in order to benefit on superior ultimate mechanical and durability properties, low permeability, low heat of hydration and thermal cracking in addition to be economically and environmentally friendly (Bilodeau and Malhotra, 2000; Şahmaran and Li, 2009; Qiang et al., 2013; Park and Noguchi, 2017; Hemalatha and Ramaswamy, 2017). However, researchers emphasize some drawbacks of the high volume fly ash

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cementitious systems such as insufficient early strength due to poor reaction rate (Lam et al., 2000; Zhang et al., 2000; Yazıcı et al., 2005; Hemalatha and Sasmal, 2018).

In recent, low carbon cements are suggested as a best option to meet the sustainability goals of cement industry (Berriel et al., 2018). Reduction in the lime saturation factor of the raw feed in the production of cement is resulted in belite-rich cement that is a low carbon cement (Lawrence, 2004). With high content of belite compound, belite-rich cement can be a suitable alternative to response abovementioned demands of the field in similar way with those of high volume fly ash systems. Gartner (2004) reported that belite compound produces approximately 4.3 times less CH product than alite compound. The reduction in CH product considerably reduces pozzolan requirement of the cements, and thus, desired benefits in the field may be achieved by lowering pozzolan content. Taylor (1990) reported that five polymorphs of belite (C_2S) exist at ordinary pressure: γ, β, α_L, α_H and α. Chemical stabilization of the reactive polymorphs of belite can be achieved by using many elements (stabilizers), of which the stabilizing effect is related to the stabilizer amount and its nature. B^{+3} is effective ion in stabilization of reactive belite phase and exhibits superior hydration kinetics when compared to Fe^{+3}, S^{+6} and K^{+} ions (Kim and Hong, 2004).

Boron active belite cement (BABC), a special type of cement produced by presence of B_2O_3 at 3–4%, allows low heat of hydration and high ultimate strength (Aydın et al., 2018). In general, byproduct of boric acid and borate is used for production of its clinker (Yeşilmen and Gürbüz, 2012; Kunt et al., 2015). Lower $CaCO_3$ content in belite cement production results in reduced decarbonation, and thus lower CO_2 and NO_x emissions (Kacimi et al., 2009). Additionally, production process of BABC facilitates reduction in energy consumption and CO_2 emission up to 25% (Saglık et al., 2008). Replacing alite clinker by reactive belite clinker allows improvement of long-term strength by decreasing $Ca(OH)_2$ content formed during its hydration, and consequently increases durability (Kacimi et al., 2009). High temperature playing an important role in nuclear reactor shields is one of the most important physical deterioration processes that influences durability of concrete structures (Morsy et al., 2012), and reduces density and shielding capabilities (for both gamma rays and neutrons) of concrete products (Sakr and El-Hakim, 2005; Yousef et al., 2008). It is well-known that fire resistance of cementitious systems is considerably affected by cement type and fly ash content (El-Didamony et al., 2012; Lublóy, 2018). Mineral admixtures can help to the development of microstructure by means of pozzolanic reaction, and thus the stabilization of $Ca(OH)_2$ released during cement hydration results in higher high-temperature resistance (Morsy et al., 2012). In consequent, BABC may be a multi-featured material in cement and concrete technology in point of both producing energy-efficient low carbon cements and ensuring neutron shielding ability.

In this study, neutron shielding performance of energy-efficient cements; boron active belite cement (BABC) and Portland composite cement (PCC), were theoretically characterized at various fly ash introduction levels by using elemental fractions of the blended cements. Additionally, high temperature resistance of the cement mortars was tested up to 900 °C in terms of compressive strength and flexural strength.

2. Materials and methods

2.1. Materials

Boron active belite cement (BABC) was produced in the Göltaş Cement Plant in Turkey. CEM II/B-M (P-L) 32.5 R type portland-composite cement (PCC) supplied from Baştaş Cement Inc. was used as alternative low heat cement in accordance with EN 197-1 (2011). Type F fly ash (FA) used in the study was obtained from Yatağan Power Plant in Turkey. Chemical and physical properties of the binders are presented in Table 1.

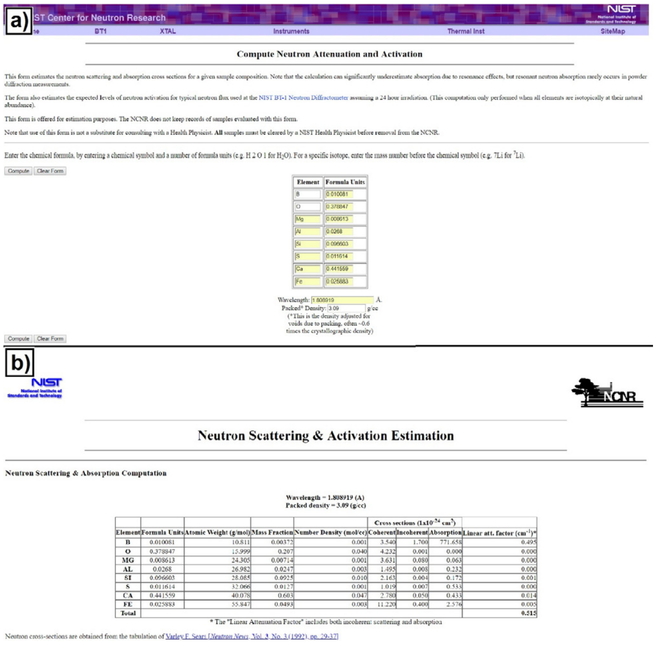
Table 1
Chemical and physical properties of binders.

Composition (%)	BABC (Sağlık et al., 2009)	PCC	FA
SiO_2	19.1	32.31	45.38
Al_2O_3	4.68	7.05	19.74
Fe_2O_3	3.42	3.30	7.47
CaO	57.1	47.33	15.22
B_2O_3	3.0	–	–
MgO	1.32	1.21	2.79
SO_3	2.68	2.72	5.63
Na_2O	0.34	1.30	0.57
K_2O	0.78	1.07	2.24
LOI*	3.82	2.47	0.87
Fineness, cm^2/g	3562	4198	3392
Density, g/cm^3	3.09	2.98	1.940

2.2. Methods

In this study, neutron attenuation characteristics of BABC and PCC were assessed for various FA replacement levels (0, 10, 20 and 30% by weight of cement). The linear neutron attenuation factors including both incoherent scattering and absorption were theoretically calculated with the help of the online NCNR (2005) computation program at 25 meV (corresponds to 1.809 Å-wavelength) for simulating attenuation of thermal neutrons. Fig. 1 presents an example given user interfaces of the online computation program used on calculation of neutron attenuation factors. Moderating materials that are elements with low atomic number (≤16) slow down and absorb neutrons (NCRP, 1957). Thus, linear neutron attenuation factors were related with moderator fractions of the blended cements in this study.

In addition to control mixtures without FA, mortar series were prepared by replacing 10%, 20% and 30% cement with FA (by weight). These mixtures were designated consecutively by the type



Compute Neutron Attenuation and Activation

This form estimates the neutron scattering and absorption cross sections for a given sample composition. Note that the calculation can significantly underestimate absorption due to resonance effects, but resonant neutron absorption rarely occurs in powder diffraction measurements.

The form also estimates the expected levels of neutron activation for typical neutron flux used at the NIST BT-1 Neutron Diffractometer assuming a 24 hour irradiation. (This computation only performed when all elements are isotopically at their natural abundance).

This form is offered for estimation purposes. The NCNR does not keep records of samples evaluated with this form.

Note that use of this form is not a substitute for consulting with a Health Physicist. **All** samples must be cleared by a NIST Health Physicist before removal from the NCNR.

Enter the chemical formula, by entering a chemical symbol and a number of formula units (e.g. H 2 O 1 for H_2O). For a specific isotope, enter the mass number before the chemical symbol (e.g. 7Li for ^7Li).

Element	Formula Units
B	0.010081
O	0.378847
Mg	0.008613
Al	0.0268
Si	0.096603
S	0.011614
Ca	0.441559
Fe	0.025883

Wavelength: 1.808919 Å.
Packed* Density: 3.09 g/cc
(*This is the density adjusted for voids due to packing, often ~0.6 times the crystallographic density)

Neutron Scattering & Activation Estimation

Neutron Scattering & Absorption Computation

Wavelength = 1.808919 (A)
Packed density = 3.09 (g/cc)

					Cross sections ($1x10^{-24}$ cm^2)			
Element	Formula Units	Atomic Weight (g/mol)	Mass Fraction	Number Density (mol/cc)	Coherent	Incoherent	Absorption	Linear att. factor (cm^{-1})*
B	0.010081	10.811	0.00372	0.001	3.540	1.700	771.658	0.495
O	0.378847	15.999	0.207	0.040	4.232	0.001	0.000	0.000
MG	0.008613	24.305	0.00714	0.001	3.631	0.080	0.063	0.000
AL	0.0268	26.982	0.0247	0.003	1.495	0.008	0.232	0.000
SI	0.096603	28.085	0.0925	0.010	2.163	0.004	0.172	0.001
S	0.011614	32.066	0.0127	0.001	1.019	0.007	0.533	0.000
CA	0.441559	40.078	0.603	0.047	2.780	0.050	0.433	0.014
FE	0.025883	55.847	0.0493	0.003	11.220	0.400	2.576	0.005
Total								0.515

* The "Linear Attenuation Factor" includes both incoherent scattering and absorption

Neutron cross-sections are obtained from the tabulation of Varley F. Sears [*Neutron News*, Vol. 3, No. 3 (1992), pp. 29-37]

Fig. 1. User interfaces for data input (a) and analysis (b) of computation program.

Table 2
Mix proportions.

Mix ID	Cement, g	Fly ash, g	Aggregate, g	Water, g	Net w/b ratio	Superplasticizer amount, %[a]
B0	450	0	1350	225	0.5	–
B10	405	45	1350	225	0.5	0.1
B20	360	90	1350	225	0.5	0.4
B30	315	135	1350	225	0.5	0.6
P0	450	0	1350	225	0.5	–
P10	405	45	1350	225	0.5	0.2
P20	360	90	1350	225	0.5	0.5
P30	315	135	1350	225	0.5	0.8

[a] By weight of binder content.

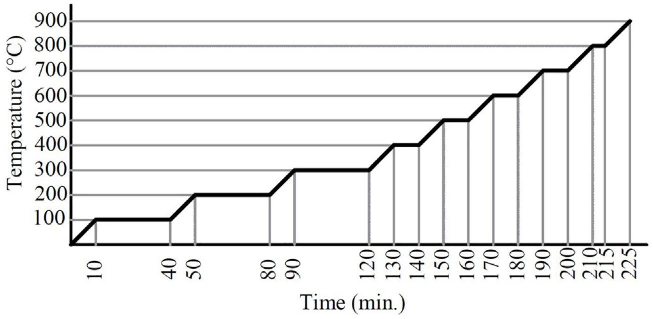


Fig. 2. Heating program of furnace.

of cement and the amount of the FA used, for example, the BABC mortar mixture at 10% FA content was designated as B10. Mix proportions of the mortars prepared in this study are given in Table 2.

Mortar mixtures were kept in constant consistency by using polycarboxylate-based superplasticizer in varying amounts. Thus, the needed water corrections were done to keep constant the w/b ratios of the mixtures. Mortar mixtures were placed into standard prisms (40 × 40 × 160 mm) by using vibrating table in two layers. The samples were demolded after 24 h and cured in tapping water until the testing time (7, 28 and 90 days) at 20 ± 2 °C.

In the study, effect of curing time and fly ash introduction on the high temperature performance of the mortars were researched. Specimens were placed into the chamber of cooled furnace in laboratory conditions at 20 °C. Then, the specimens were exposed to targeted elevated temperatures for 1 h after furnace reached to the temperatures. Mortar series without FA were exposed to 100, 300, 500, 700 °C at 7, 28 and 90-day curing periods. Moreover, mortars having 0, 10, 20 and 30% FA (by weight of cement) were examined at 100, 300, 500, 700 and 900 °C at 90-day curing period. Cooling time was enough prolonged to avoid thermal shock effect on specimen. Heating program of furnace having 1800 °C-heating capacity is shown in Fig. 2 up to 900 °C.

EN 196-1 (2016) was followed in preparation and mechanical tests (compressive strength and flexural strength) of mortar prisms (40 × 40 × 160 mm). The compressive strength tests were performed on six pieces (40 × 40 × 40) left from flexural strength test of the prisms.

3. Results and discussion

3.1. Some characteristics of cement pastes

Consistency, setting time and soundness of cements containing 0, 10, 20 and 30% FA (by weight of cement) were given in Table 3. In general, FA introduction retarded initial setting time, and deteriorated soundness of the cement pastes.

3.2. Neutron shielding characteristic of cements

Elemental fractions and densities of all cements are presented in Table 4. Linear neutron attenuation factors of the cements were calculated by considering the characteristics of cements.

Linear neutron attenuation factors and relative variation values are given in Fig. 3a for BABC, and in Fig. 3b for PCC according to FA replacement amount. Linear attenuation factors were found as 0.515 cm^{-1} for BABC, and 0.021 cm^{-1} for PCC. FA introduction considerably reduced (up to 34%) the linear attenuation factors of BABC due to reduction in boron fraction. However, FA caused slight reductions (up to 4%) in the linear attenuation factors of PCC. A linear relationship ($R^2 \approx 1$) was constituted between FA replacement level and the linear attenuation factors for both cement types.

Relationships between linear attenuation factor and moderator fraction of cements are given in Fig. 4a. And, Fig. 4b presents the ratio of the linear attenuation factors of BABC to those of PCC at each FA replacement content to emphasize the shielding efficiency of BABC according to those of PCC. There is a good relation between moderator fractions and the attenuation factors of the cements. Neutron shielding ability of BABC was found 25 times higher than that of PCC. FA introduction reduced the neutron attenuation efficiency of BABC. Especially, at 30% FA content, the linear attenuation factor of BABC was found almost 17 times higher than that of PCC. Thus, in this shielding efficiency perspective, BABC should be blended with minimum FA introduction allowing the required

Table 3
Physical characteristics of cements.

Cement type	FA replacement (%)	Consistency (%)	Initial setting (min)	Final setting (min)	Soundness (mm)
BABC	0	24.2	145	315	1.0
	10	24.6	150	325	2.0
	20	25.0	185	325	2.0
	30	25.4	225	335	4.5
PCC	0	25.6	60	210	1.0
	10	26.2	60	215	3.0
	20	27.0	75	215	4.5
	30	27.8	100	235	5.0

Table 4
Elemental fractions and densities of cements.

Element	Atomic number (Z)	Boron active belite cement (BABC)				Portland composite cement (PCC)			
		0% FA (ref)	10% FA	20% FA	30% FA	0% FA (ref)	10% FA	20% FA	30% FA
B	5	0.0101	0.0091	0.0081	0.0071	0.0000	0.0000	0.0000	0.0000
O	8	0.3691	0.3777	0.3862	0.3948	0.3910	0.3974	0.4037	0.4101
Na	11	0.0027	0.0029	0.0031	0.0032	0.0100	0.0094	0.0089	0.0083
Mg	12	0.0086	0.0095	0.0104	0.0112	0.0076	0.0086	0.0095	0.0105
Al	13	0.0268	0.0339	0.0410	0.0481	0.0388	0.0446	0.0505	0.0564
Si	14	0.0966	0.1088	0.1209	0.1331	0.1568	0.1630	0.1691	0.1752
S	16	0.0116	0.0128	0.0139	0.0151	0.0113	0.0125	0.0137	0.0149
K	19	0.0070	0.0082	0.0094	0.0106	0.0092	0.0102	0.0112	0.0122
Ca	20	0.4416	0.4086	0.3756	0.3427	0.3513	0.3274	0.3034	0.2795
Fe	26	0.0259	0.0287	0.0315	0.0342	0.0240	0.0269	0.0299	0.0329
Total		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Density, g/cm^3		3.090	2.975	2.860	2.745	2.980	2.876	2.772	2.668
Moderator fraction ($Z \leq 16$)		0.523	0.555	0.583	0.612	0.616	0.635	0.655	0.675

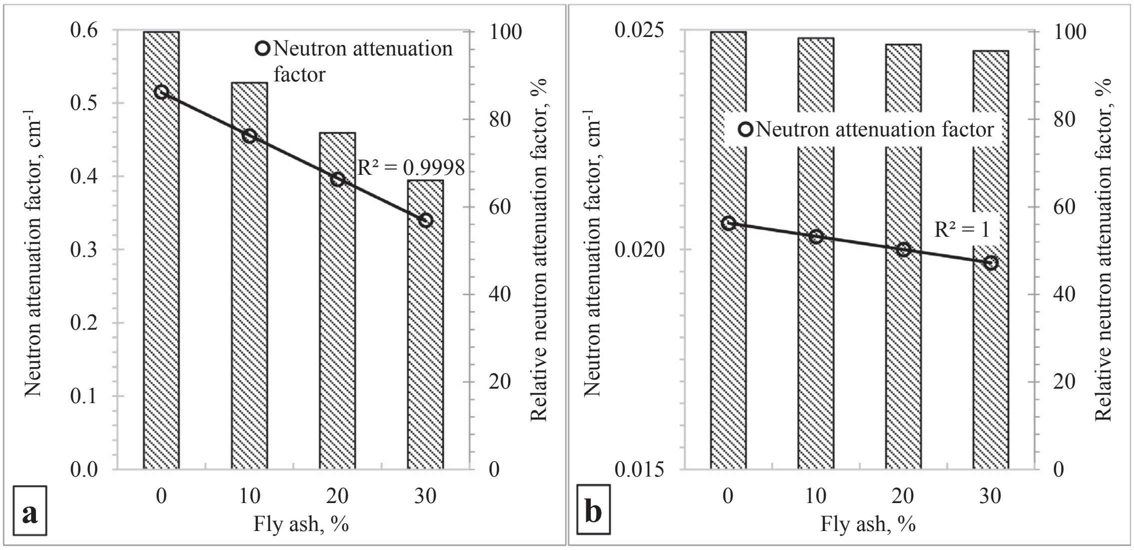


Fig. 3. Linear neutron attenuation factors and relative values for BABC (a) and for PCC (b).

performance in terms of durability, strength, permeability, fire and aggressive environment resistance, etc.

3.3. Effect of curing time and fly ash content on the compressive strength of mortars

The compressive strength results of BABC and PCC mortars are presented in Fig. 5a up to 90 days. The results of the BABC were found to some extent higher than PCC at all curing ages. 7 and 90-day compressive strength values of the mortars are given as relative in Fig. 5b by considering that of 28-day (100%). There are small strength variations between the both cements, and thus, effect of the difference were ignored on the assessment of this study results. Elongated curing time (90-day) considerably increased (27–31%) the compressive strength values of both cement types according to 28-day results. Gökçe et al. (2012) reported that strength development of boron active belite cement and Portland composite cement is more pronounced at later curing ages (up to 1 year) than that of ordinary portland cement.

Ultimate compressive strength values (90-day) of the cement mortars are presented in Fig. 6a according to FA replacement level. Moreover, relative compressive strength values (%) of the mortars are given in Fig. 6b by considering that of reference mixtures without admixture as 100% in order to mention the effect of fly ash. FA introduction reduced the compressive strength values of the BABC and PCC mortars. 10% FA introduction caused a more pronounced reduction in compressive strength of BABC mortars than that of PCC. The reductions of PCC were found more remarkable at the highest content of FA (30%). Unlike to results of this study, it is known that such fly ash introduction can cause slight variations (from 8% reduction to 6% increment) in compressive strength of ordinary portland cement mortars at 90-day curing time (Papadakis, 1999; Chindaprasirt and Rukzon, 2008). In this study, the high reductions in compressive strength values are possibly caused by the less reactivity of belite polymorphs in BABC, and by less retained ordinary clinker proportion in PCC. Thus, such mixtures need elongated curing regimes in presence of FA.

3.4. Effect of high temperature on various curing periods

Effect of high temperatures (up to 700 °C) on compressive strength and flexural strength of cement mortars is given for 7, 28 and 90-day curing periods in Fig. 7a and Fig. 7b, respectively. It was observed that high temperatures caused more damage on the flexural strength results when compared to compressive strength of mortars. The variation can be resulted from the destructive

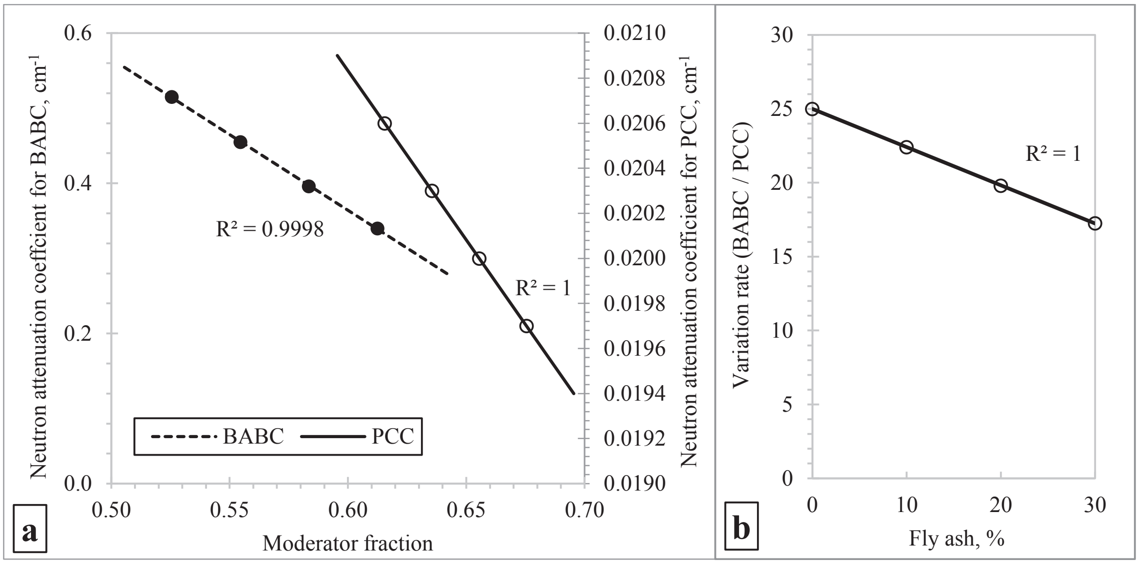


Fig. 4. Relation between moderator fraction and linear attenuation factor (a) and shielding efficiency of BABC (b).

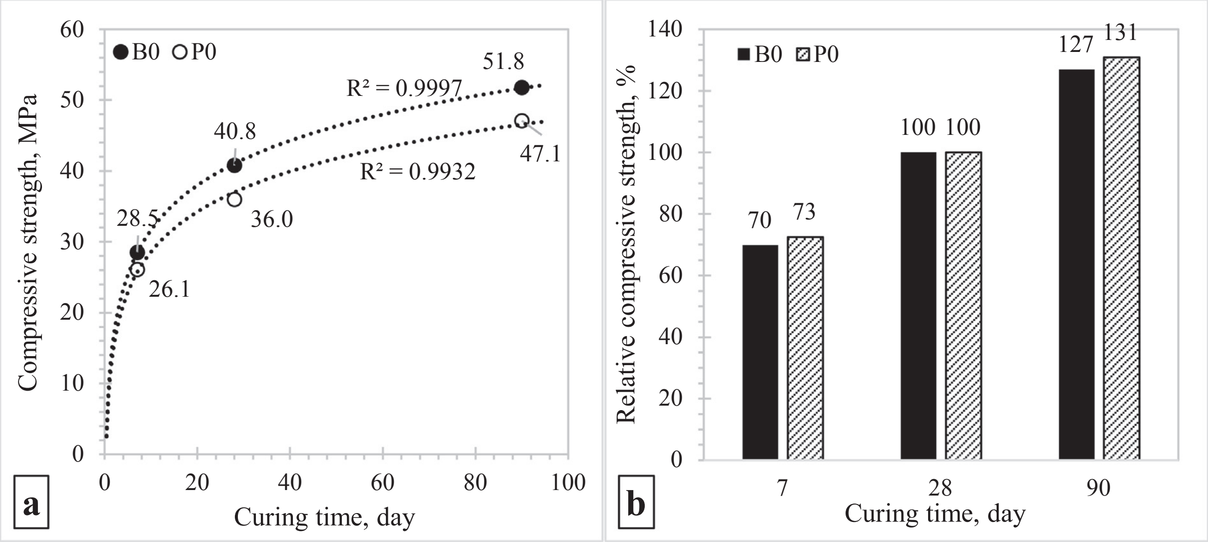


Fig. 5. Effect of curing time on compressive strength (a) and relative compressive strength (b).

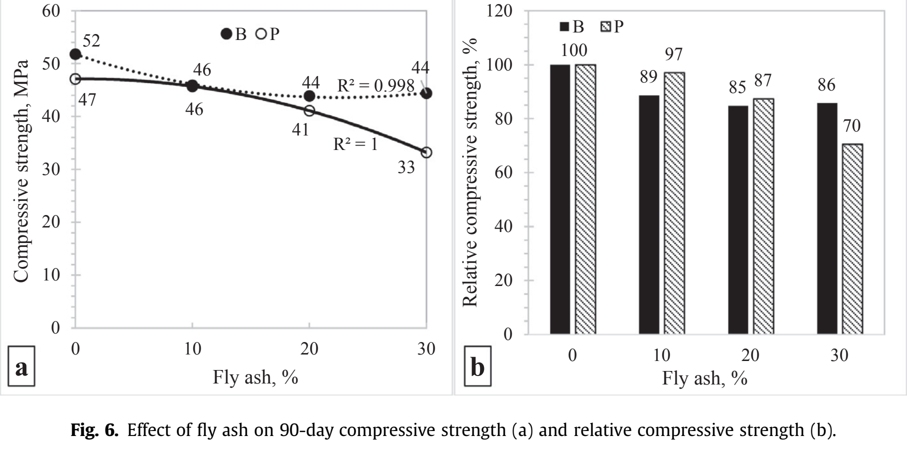


Fig. 6. Effect of fly ash on 90-day compressive strength (a) and relative compressive strength (b).

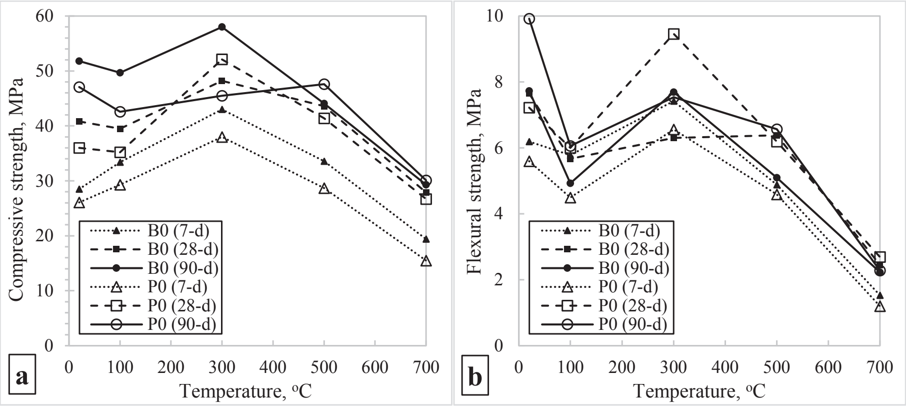


Fig. 7. Effect of high temperature on compressive strength (a) and flexural strength (b) at various curing periods.

effects of micro-cracks formed at elevated temperatures on tension rather than compression (Cülfik and Özturan, 2002).

Effect of high temperatures on relative compressive strength values of mortars is given for 7, 28 and 90-day curing periods in Fig. 8a by considering those of mortars at 20 °C as 100%. Moreover, residual compressive strength rates of the mortars at 700 °C are presented in Fig. 8b according to original compressive strength values of the mortars non-exposed to high temperature. At 7-day specimens, relative compressive strength of BABC mortar remarkably increased (up to 51%) by increasing temperatures up to 300 °C. At the same conditions, similar strength gain (up to 46%) was observed in the PCC mortars. At 28-day specimens, relative compressive strength increment (45%) of PCC mortars was found significantly higher at 300 °C than that (18%) of BABC mortars. At 90-day specimens, BABC mortars showed less resistance to high temperatures at 500 and 700 °C unlike to at 100 and 300 °C when compared to that of PCC mortars. While residual compressive strength of BABC mortar at 700 °C was found higher at early curing time (7 days), PCC mortars were resulted in higher residual compressive strength results at later ages (28 and 90 days).

Significant increments (up to 51%) in compressive strength of the mortars at 300 °C express the slow reaction of BABC and PCC in the study. Such high temperatures accelerate the hydration of the cements especially at 7-day curing time. Micro-cracks are not formed in either hardened cement phase or interfacial transition zone up to 200 °C (Lin et al., 1996; Li et al., 1999). Hydration of unhydrated cement grains is improved by steam effect of internal autoclaving condition and evaporation of water at 300 °C in particularly high strength concrete with high resistance to moisture flow (Saad et al., 1996; Ma et al., 2015). Moreover, increase in compressive strength can be observed by the hydration of anhydrated pozzolan particles which are activated with temperature rise (Morsy et al., 2008). Therefore, compressive strength of concrete keeps constant, or even slightly increases up to 300 °C (Ma et al., 2015). However, hydration products, CH and C-S-H, are decomposed almost at 450 °C and over temperatures (Morsy et al., 2010; Heikal et al., 2013). Thus, compressive strength of the cementitious systems significantly reduces after the certain temperatures.

3.5. Effect of high temperature at various fly ash content

Effect of high temperatures (up to 900 °C) on ultimate compressive strength (90-day) and flexural strength values of cement mortars containing FA is given in Fig. 9a and Fig. 9b, respectively. It was observed that high temperatures caused more damage on the flexural strength results when compared to compressive strength of mortars. Because destructive effects of micro-cracks formed at elevated temperatures are more pronounced on tension rather than compression as stated before (Cülfik and Özturan, 2002), reduction in flexural strength values is more than compressive strength values.

Effect of high temperatures on ultimate compressive strength values of mortars containing FA is relatively given for BABC in Fig. 10a, and for PCC in Fig. 10b by considering the mortars non-exposed to elevated temperatures as 100%. 30% FA introduction impaired the ultimate compressive values of BABC mortar at elevated temperatures. 10% and 20% FA introduction can be a

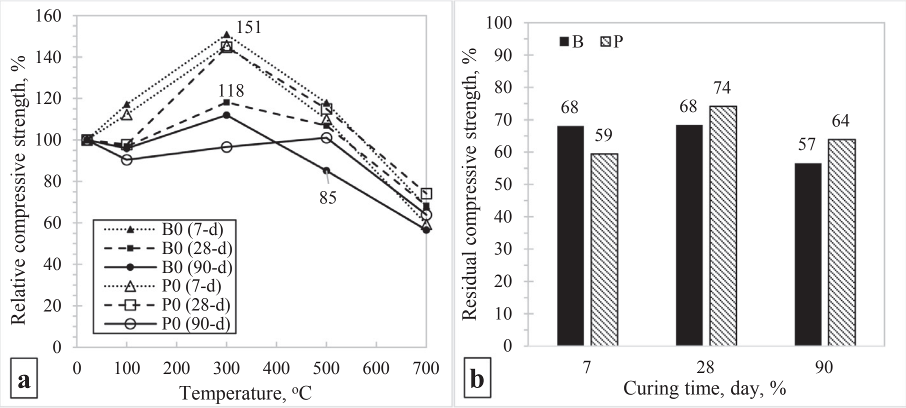


Fig. 8. Effect of high temperature on relative compressive strength (a) and residual compressive strength at 700 °C (b).

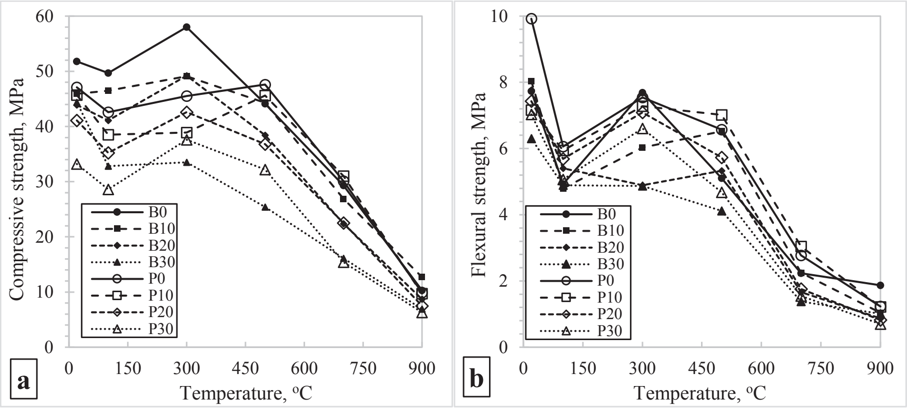


Fig. 9. Effect of high temperature on ultimate compressive strength (a) and ultimate flexural strength (b) of mortar with and without FA.

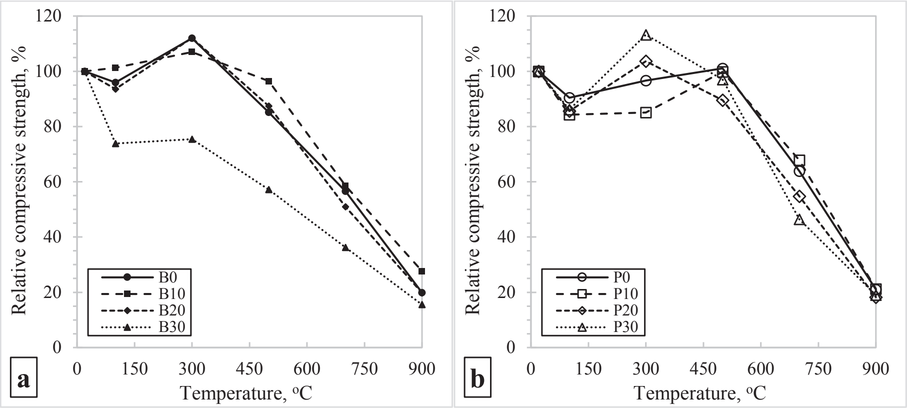


Fig. 10. Effect of high temperature on relative compressive strength of BABC mortar (a) and PCC mortar (b) at various FA content.

suitable amount for BABC thanks to its slight variation effect on ultimate compressive strength values. 20 and 30% FA introduction improved the high temperature resistance of PCC mortar at 300 °C unlike at 700 °C. Mineral admixtures can help to the development of microstructure by means of pozzolanic reaction, and thus the stabilization of CH released during cement hydration can improve the high-temperature resistance (Morsy et al., 2012). On the other hand, belite compound produces significantly less CH product than alite compound (Gartner, 2004). The reduction in CH product will considerably reduce pozzolan requirement in such cements. Therefore, reduction in compressive strength results at elevated temperatures showed that 30% FA content is higher for BABC mortars in this study. Similarly, Heikal et al. (2013) reported that overdose FA impaired the high temperature resistance of portland cement mortars.

Effect of FA on relative compressive strength of mortars exposed to 900 °C is presented in Fig. 11a by considering the mixtures without FA as 100%. 10% FA introduction in BABC mortar improved its resistance to high temperature at 900 °C. Moreover, reductions in compressive strength of mortars were found more pronounced in PCC mortars at 20 and 30% FA introduction according to BABC mortars. Thus, FA in low replacement level (10%) is promising for mortars exposed to such temperatures. Residual compressive strength values of the mortars at 900 °C are given in Fig. 11b according to original compressive strength values of the mortars non-exposed to high temperature. The residual compressive strength of BABC mortar at 900 °C was found more satisfactory at 10% FA introduction than those of BABC and PCC mortars with and without FA. However, out of the satisfactory result, FA introduction at any replacement level slightly affected on the residual compressive strength values (16–21%) of mortars at 900 °C. Because gehlenite is formed in portland cement mortars containing FA at 900 °C, pores are filled by such phases, and interfacial transition zone is enhanced between cement matrix and aggregate (Aydin and Baradan, 2007; Aydin, 2008). Moreover, Ma et al. (2015) reported that incorporation of FA in portland cement can remain the mechanical properties of concrete at a higher level after exposing to 900 °C.

Hertz (2005) expressed that concrete can recover itself at temperatures below 300 °C by the absorbing moisture from air, while strength loss is permanent when the micro-cracks is formed. Such strength loss of mortars observed in this study might have accompanied by significant weight loss as known from the results presented by Arioz (2007) and Sancak et al. (2008). The weight loss can reach up to 20% in hydrated ordinary Portland cement paste at 900 °C (Arioz, 2007). Hertz reported that the reductions are caused by the released of physically and chemically bound water from hydrated cement product (Hertz, 2005). The loss in weight and H fraction that is an important neutron moderator can significantly impair the radiation shielding efficiency against gamma rays and neutrons at high temperatures. Yousef et al. (2008) reported that loss in strength and density of concrete mixtures is accompanied by loss in neutron and gamma-ray attenuation ability. Thus, high residual strength of the mortars in the study is an indication of higher hydrogen retention ability and better neutron shielding performance at high temperature cases.

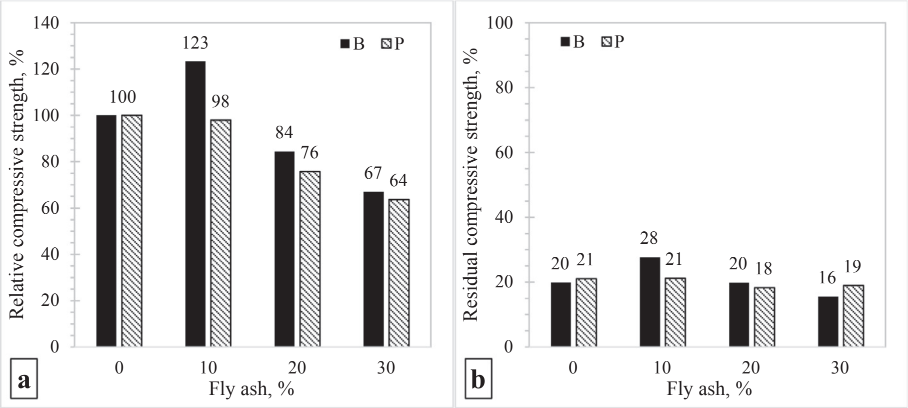


Fig. 11. Effect of FA on relative compressive strength (a) and residual compressive strength (b) at 900 °C.

3.6. Detail of statistical analysis for flexural and compressive strength results

In this study, flexural strength results of cement mortars were determined on three prism specimens. The compressive strength test was performed on the halves of the broken prism specimens according to EN 196-1 (2016). Thus, compressive strength test was repeated on six specimens for each mortar series. Coefficient of variance (CoV) of flexural strength results and compressive strength results was reach up to 21% and 9%, respectively. Flexural strength results performed according to EN 196-1 (2016) may not be similar due to inconsistent broken prisms in three-point method, especially in low strength values. In general, CoV values of the mortar series were found higher when the specimens exposed to high temperatures in this study.

4. Conclusions

Cement industry has recently focused on the sustainability of its products in terms of economic and ecologic awareness. Boron active belite cement can support the sustainability gains in addition to superior shielding performance against neutrons. Because fire plays an important role on shielding and mechanical performance of the cementitious products, their resistances to high temperatures is needed to be research. The following conclusions can be drawn about neutron attenuation capability of boron active belite cement and Portland composite cement, and high temperature performance of their mortars containing fly ash in the study:

- The neutron attenuation factor of boron active belite cement was found 25 times higher than that of portland composite cement. Fly ash introduction significantly decreased the neutron attenuation factor of boron active belite cement due to causing major reduction in boron fraction of the blended cements. Thus, the shielding performance reduced from 25 times to 17 times by the introduction of fly ash from 0% to 30%, respectively.
- It is clear from the study that effect of high temperature is more destructive on the flexural strength of mortar prism when compared to compressive strength.
- 7 and 28-day compressive strength values of mortars without fly ash remarkably improved at 300 °C. Residual compressive strength values of the boron active belite cement mortars exposed to 700 °C were found poorer than those of portland composite cement at 28 and 90-day.
- 10% fly ash introduction remarkably increased (23%) the resistance of boron active belite cement mortar exposed to 900 °C. 30% fly ash introduction significantly reduced the high temperature resistance of boron active belite cement mortars. Residual compressive strength of boron active belite cement mortars at 900 °C was found higher than portland composite cement at 10% fly ash introduction. 20% fly ash introduction in mortars showed almost similar residual results to those of mortars without fly ash at 900 °C. However, 30% fly ash introduction reduced the residual results in boron active belite cement mortar.
- Author of the study recommends use of boron active belite cement in heavyweight concrete production instead of ordinary portland cement to improve the simultaneous shielding efficiency for neutrons and gamma rays. Additionally, mechanical performance of the cement is promising up to 300 °C at even 10 and 20% fly ash introductions, thus it can be a satisfactory alternative for coating of nuclear reactor or radioactive sources.

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