

# Effect of blended cements produced with natural zeolite and industrial by-products on alkali-silica reaction and sulfate resistance of concrete

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## ABSTRACT

In this study, influence of blended cements produced with different types of pozzolans on alkali-silica reaction (ASR) and sulfate resistance of concrete was investigated. For this reason, natural zeolite (clinoptilolite), fly ash (FA), and ground granulated blast furnace slag (GBFS) were used in different types of blended cement production. According to the mechanical performance of these blended cements, ASR and sulfate resistance experiments were carried out to obtain the durability performance of these cements. The length changes and microstructure investigations of the mortar specimens with different types of blended cements showed that zeolite, FA, and GBFS had reduced ASR and sulfate damages when compared with ordinary CEM I 42.5 reference specimen.

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## 1. Introduction

Concrete is one of the most widely used construction material, owing to its good durability to cost ratio. However, when subjected to severe environments, its durability can significantly decline due to corrosion of the embedded reinforcement and/or degradation of the concrete [1]. The most important parameter on concrete performance is the properties of cement used in concrete production. It is possible to achieve environmental and economical benefits with the utilization of pozzolanic mineral additives in cement production. The durability problems in concrete and reinforced concrete structures exposed to aggressive environment effects lead to damages in the structures before the expected service life. It is generally recognized that addition of pozzolan reduces the calcium hydroxide content in cement paste and improves the permeability of concrete [2]. The most important concerns in the design of durable concrete are alkali-silica reaction (ASR) and sulfate attack.

The use of certain aggregates in concrete may result in a chemical process, in which particular constituents of the aggregates react with alkali hydroxides present in the concrete pore solution [3]. Damage to concrete structures due to ASR and the consequent expansion is being observed in more and more countries [4]. ASR causes premature deterioration in concrete. Alkali hydroxides present in the concrete pore solution react with amorphous or poorly crystalline silica phases in aggregates, forming a gel that imbibes water and expands [5]. The expansive pressure generated by

the hydrated alkali silicate has been widely believed to induce cracking and deterioration of concrete. However, this notion may not be necessarily correct. Concrete is a porous material and the hydrated alkali silicate is rheologically a fluid material that can slowly diffuse into the pores and preexisting cracks to loose its expansive pressure. The diffused alkali silicate has been proposed to generate an expansive pressure by reacting with  $\text{Ca}^{2+}$  ions [6].

Deterioration of concrete by sulfate attack is commonly observed in structures exposed to soils or groundwater containing high concentration of sulfate ions [7]. Sodium sulfate reacts with calcium hydroxide to form calcium sulfate (gypsum). This reaction proceeds to a greater or lesser extent, depending on the conditions [8]. Owing to the penetration of sulfate ions into the concrete, the calcium monosulfoaluminate crystals in the paste may convert into gypsum or ettringite; this results in a change to a larger molar volume. These volumetric changes cause expansion and internal stresses, which ultimately weaken and destroy the paste bonds, deteriorating the concrete [9]. Calcium hydroxide has several damaging attributes with regard to sulfate resistance of concrete. It directly reacts with sulfate ions to produce gypsum; the acidic nature of sulfate solutions favors this reaction, resulting in softening of the cement paste [10]. To mitigate this attack, concrete codes recommend a concrete mixture with low water/cement ratio and containing a sulfate-resistant Portland cement. The lowered availability of  $\text{C}_3\text{A}$  can reduce the damage caused by sulfate attack due to a direct reduction in the quantity of ettringite that can form. Furthermore, ettringite formation in chloride-rich environments is not associated with expansion and cracking [11].

Zeolites are crystalline alumina silicates with uniform pores, channels, and cavities. They possess special properties, such as

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ion exchange, molecular sieves, a large surface area, and catalytic activity, which makes them a preferable material for tremendous industrial applications [12]. In the recent years, rather than the known application areas, many researches [13] concerning the use of natural zeolite, especially clinoptilolite in concrete applications, such as pozzolanic cement, light-weight aggregates, and dimension stone, could be observed. Zeolitic tuffs and amorphous silicate tuffs are the main natural pozzolans in the cement industry. The pozzolanic activity of zeolites (Z) depends on their chemical and mineralogical composition. The pozzolanic properties of Z are due to their reactive  $\text{SiO}_2$  and  $\text{Al}_2\text{O}_3$ , which react with calcium hydroxide liberated during the hydration of cement, and convert it into C–S–H gels and aluminates. As a result, the microstructure of hardened cement concrete is improved and the concrete becomes more impervious [14]. On the other hand, some materials, such as fly ash (FA) and ground granulated blast furnace slag (GBFS) can be used as supplementary cementing material or artificial pozzolan in concrete industry. The reactivity of FA and GBFS is supposed to be particularly influenced by the glass content and its composition.

In this study, the influence of blended cements produced with different types of pozzolans on ASR and sulfate resistance of concrete was investigated. For this reason, natural zeolite (clinoptilolite) and two different types of industrial by-products (FA and GBFS) were used in blended cement production. The length changes and mechanical properties of the mortar specimens with different types of blended cements were determined and analyzed to obtain a durable cement composition against ASR and sulfate attack.

## 2. Experimental study

### 2.1. Materials and methods

The raw materials of blended cement compositions were obtained from different sources. Cement clinker, gypsum, and limestone were purchased from Çimsa Eskişehir cement factory. Natural zeolite in clinoptilolite form was obtained from Manisa Gördes region. The industrial by-products, FA and GBFS, were obtained from Kütahya Tunçbilek Thermal Power Plant and Ereğli Iron and Steel Factory, respectively.

**Table 1**  
Chemical composition of the raw materials.

| Chemical composition    | Clinker (%) | Clinoptilolite (%) | FA (%) | GBFS (%) |
|-------------------------|-------------|--------------------|--------|----------|
| $\text{SiO}_2$          | 20.98       | 62.78              | 61.12  | 35.11    |
| $\text{Al}_2\text{O}_3$ | 5.55        | 10.66              | 12.32  | 17.63    |
| $\text{Fe}_2\text{O}_3$ | 3.85        | 4.20               | 6.51   | 0.35     |
| CaO                     | 65.85       | 2.37               | 4.28   | 37.56    |
| MgO                     | 1.12        | 1.10               | 5.88   | 5.52     |
| $\text{K}_2\text{O}$    | 0.53        | 0.74               | 1.73   | –        |
| $\text{Na}_2\text{O}$   | 0.14        | 0.35               | 2.44   | 0.32     |
| $\text{SO}_3$           | 0.97        | –                  | 0.1    | –        |
| LOI <sup>a</sup>        | 2.23        | 12.40              | 0.84   | 0.75     |

<sup>a</sup> LOI: loss on ignition.

In this study, 24 different types of blended cement mixes with Z, FA, and GBFS, replacement of 10%, 20%, 30%, 40%, and 45% by weight, 5% limestone for particle size arrangement, and 3% gypsum were produced by intergrinding these materials in ball mill. These were defined as the first group. According to compressive strength test results of the first-group cements, the optimum replacement ratio of additives was found as 20% and 30% of the clinker. Subsequently, the second-group mixes were designed by means of 20% and 30% replacement ratio as binary composition. In addition one type of blended cement (ZFSBC) was produced as triple composition by replacing both of Z, FA and GBFS in 10% replacement ratio. These blended cements were compared with reference to CEM I 42.5 ordinary Portland cement in experimental studies [15]. According to the mechanical test results of the blended cements, durability tests were performed on seven different types of blended cements. ASR experiments were carried out in accordance with ASTM C 1260 code [16]. Mortar bars were prepared in the dimensions of  $25 \times 25 \times 285$  mm to determine the length change of different types of the produced blended cements. The aggregate used in cement mortar preparation was a mix of two kinds of sand to obtain a reactive silica environment in the hardened mortar specimens. These aggregates were reactive glass sand and standard Rilem sand, and mixed together as 50 wt%. The aggregates grain distribution was balanced in accordance with ASTM C 1260 code. Mortar bar specimens were initially cured in the curing cabinet for 24 h, and subsequently cured in lime-saturated water at  $80^\circ\text{C}$  for 24 h. Afterwards, the specimens were immersed in 4% NaOH solution at  $80^\circ\text{C}$  for 14 days. The comparator readings of the mortar bars were carried out at 4, 8, and 14 days.

Sulfate resistance of the blended cements were determined on the mortar bars prepared according to ASTM C 1012, in dimensions of  $25 \times 25 \times 285$  mm [17]. After the initial curing period, the specimens were demolded and cured in lime-saturated water ( $23 \pm 1.7^\circ\text{C}$ ) until the  $40 \times 40 \times 160$ -mm mortar specimens gained a compressive strength of 20 MPa, as described by ASTM C 1012. Upon reaching a compressive strength of 20 MPa, the performance of the cements under sulfate attack were determined weekly through expansion measurements of mortar bars, immersed in 10%  $\text{Na}_2\text{SO}_4$  solution for 6 months. The sulfate solution's  $\text{Na}_2\text{SO}_4$  concentration was chosen as 10% to increase the aggressive effect of the sulfate environment. During this curing cycle, compressive strength and ultrasound pulse velocity (UPV) tests were carried out to determine the mechanical and physical properties of different cement types against sulfate attack.

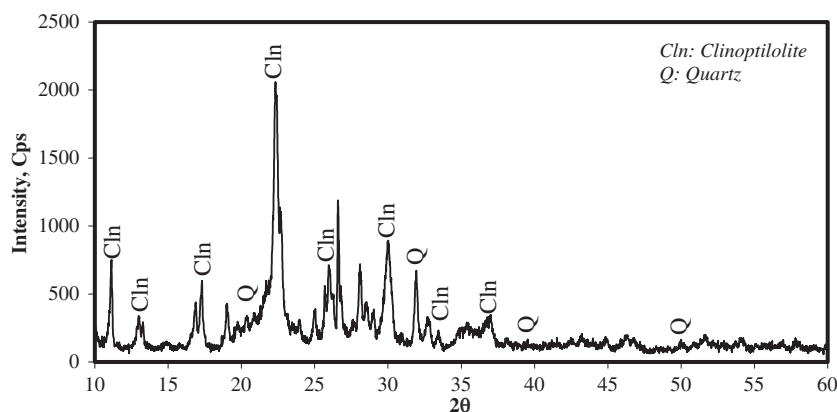
### 2.2. Characterization techniques

The prepared cement mortars with the produced cements were cast in  $40 \times 40 \times 160$ -mm prismatic molds, according to TS EN 196-1 [18]. The mortar specimens were removed from the molds after 1 day and were then cured in lime-saturated water at  $20 \pm 1^\circ\text{C}$  until the time of the considered strength test. At the end of the curing period (2, 7, 28, and 180 days), the mortar specimens were subjected to compressive strength test. The UPV tests were carried out using a non-destructive ultrasonic testing utility. Chemical analyses of the raw materials were carried out by using an XRF unit (Spectro X-Lab 2000). Mineralogical analyses of the mineral additives were conducted by using an X-ray diffractometer (XRD) (Rigaku, Rint 2200 with a nickel filtered Cu K $\alpha$ ). The microstructural evolution of bodies was observed by using versatile, analytical, ultrahigh-resolution field emission scanning electron microscope (FESEM), Zeiss Supra 50 VP, on gold-coated sections.

## 3. Evaluation of test results

### 3.1. Chemical and mineralogical analyses

The chemical analyses using XRF, which identified the main oxide compositions of the blended cement mineral additives are



**Fig. 1.** XRD analyses of zeolite.

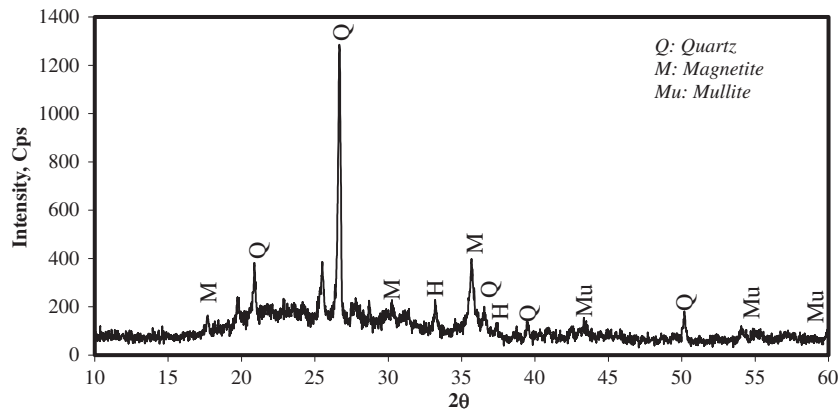


Fig. 2. XRD analysis of fly ash.

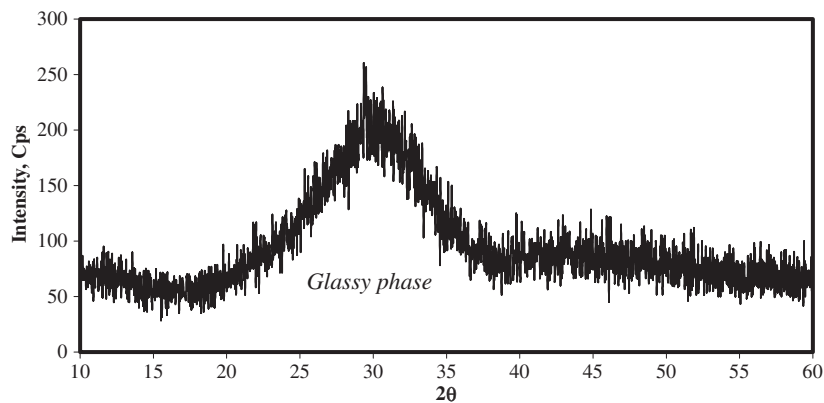


Fig. 3. XRD analysis of blast furnace slag.

given in Table 1. As shown in Table 1, natural zeolite can be classified as K-rich clinoptilolite. The  $\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$  and CaO ratio of FA was determined as 77.33% and 4.29%, respectively. According to ASTM C 618 Tuncbilek, FA can be defined as Class-F FA [19]. FA and GBFS contains high amount of silica. According to Table 1, FA is a low-calcium F-type material. The mineralogical investigation results of the additives using the XRD technique are given in Figs. 1–3. As shown in Fig. 1, Z consists of clinoptilolite, quartz, and feldspar phases. The glassy phase in Z represents the pozzola-

nic property of this material. According to Fig. 2, FA consists of glassy phase ( $2\theta = 22\text{--}24^\circ$ ), quartz, hematite, and magnetite. These results show that the pozzolanic activity is strong depending on the silicious and clear glassy structure of FA. In Fig. 3, the XRD peaks show that the GBFS consists of amorphous to poorly crystalline phases. This amorphous structure results in a good pozzolanic binding property to GBFS.

### 3.2. Compressive strength

According to compressive strength test results, the optimum usage of mineral additive in blended cement mixtures was found to be 30% replacement ratio. Therefore, sulfate resistance and ASR tests were carried on 30% blended cements. The first-group

**Table 2**  
Compressive strength of single composition blended cements.

| Cement code | Compressive strength (MPa) |        |         |          |
|-------------|----------------------------|--------|---------|----------|
|             | 2 Days                     | 7 Days | 28 Days | 180 Days |
| CEM I 42.5  | 22.0                       | 30.4   | 45.2    | 50.7     |
| ZBC-10      | 12.3                       | 22.5   | 46.9    | 57.1     |
| ZBC-20      | 11.2                       | 20.3   | 48.2    | 54.9     |
| ZBC-30      | 10.9                       | 18.5   | 45.3    | 53.0     |
| ZBC-40      | 7.2                        | 17.2   | 39.6    | 50.6     |
| ZBC-45      | 6.9                        | 15.0   | 38.1    | 48.3     |
| FBC-10      | 11.5                       | 22.0   | 44.6    | 52.9     |
| FBC-20      | 10.6                       | 21.0   | 45.4    | 58.0     |
| FBC-30      | 8.6                        | 19.5   | 41.0    | 54.9     |
| FBC-40      | 8.1                        | 18.7   | 38.5    | 50.8     |
| FBC-45      | 7.8                        | 16.4   | 37.5    | 48.7     |
| SBC-10      | 13.8                       | 35.3   | 51.6    | 54.8     |
| SBC-20      | 12.8                       | 32.2   | 52.9    | 56.3     |
| SBC-30      | 11.3                       | 29.6   | 48.2    | 59.4     |
| SBC-40      | 9.0                        | 24.8   | 45.5    | 55.0     |
| SBC-45      | 8.3                        | 23.1   | 42.8    | 53.2     |

Z: Zeolite, S: ground granulated blast furnace slag, F: fly ash.

**Table 3**  
Compressive strength of different composition blended cements.

| Cement code | Compressive strength (MPa) |        |         |          |
|-------------|----------------------------|--------|---------|----------|
|             | 2 Days                     | 7 Days | 28 Days | 180 Days |
| ZFBC-20     | 12.2                       | 25.1   | 43.7    | 52.0     |
| ZSBC-10     | 12.5                       | 27.3   | 45.5    | 60.7     |
| ZSBC-20     | 11.1                       | 24.1   | 42.5    | 51.1     |
| FSBC-10     | 13.3                       | 28.3   | 43.2    | 58.2     |
| FSBC-20     | 12.4                       | 21.8   | 40.0    | 55.6     |
| UZBC-10     | 12.6                       | 28.3   | 45.4    | 61.6     |
| UZBC-20     | 10.2                       | 24.7   | 40.8    | 54.8     |
| SFBC-20     | 13.3                       | 27.9   | 46.7    | 56.6     |
| SZBC-20     | 13.9                       | 25.8   | 44.2    | 53.8     |
| ZFSBC       | 13.6                       | 26.1   | 48.9    | 58.1     |

Z: zeolite, S: ground granulated blast furnace slag, F: fly ash.

**Table 4**  
Chemical composition of blended cements used in asr tests.

| Component (%)                  | Cement code |        |        |        |         |         |       |
|--------------------------------|-------------|--------|--------|--------|---------|---------|-------|
|                                | CEM I 42.5  | ZBC-30 | FBC-30 | SBC-30 | ZSBC-10 | FSBC-10 | ZFSBC |
| SiO <sub>2</sub>               | 20.91       | 32.80  | 28.65  | 25.01  | 26.27   | 24.59   | 29.08 |
| Al <sub>2</sub> O <sub>3</sub> | 5.44        | 7.41   | 8.31   | 7.56   | 6.94    | 7.06    | 7.77  |
| Fe <sub>2</sub> O <sub>3</sub> | 3.71        | 2.87   | 4.48   | 2.63   | 2.68    | 3.24    | 3.28  |
| CaO                            | 63.88       | 47.24  | 46.76  | 55.26  | 55.54   | 55.37   | 49.68 |
| MgO                            | 1.69        | 2.04   | 2.94   | 3.17   | 2.54    | 2.70    | 2.69  |
| P <sub>2</sub> O <sub>5</sub>  | 0.12        | 0.06   | 0.09   | 0.07   | 0.07    | 0.08    | 0.07  |
| K <sub>2</sub> O               | 1.12        | 1.42   | 1.02   | 0.79   | 0.98    | 0.85    | 1.10  |
| Na <sub>2</sub> O              | 0.45        | 0.34   | 0.36   | 0.36   | 0.33    | 0.35    | 0.33  |
| SO <sub>3</sub>                | 2.84        | 2.46   | 2.79   | 2.98   | 2.99    | 3.11    | 2.72  |
| Cl <sup>-</sup>                | 0.012       | 0.011  | 0.011  | 0.012  | 0.012   | 0.012   | 0.011 |
| EAC <sup>a</sup>               | 1.19        | 1.17   | 1.03   | 0.87   | 0.97    | 0.91    | 1.05  |

<sup>a</sup> EAC: equivalent alkali content.

blended cements' compressive strength test results are given in Table 2. From Table 2, it can be observed that early-age strength development of GBFS-blended cements are better than Z- and FA-blended cements. Furthermore, it can be concluded that 20% and 30% replacement ratio of mineral additive is the optimum usage of Z-, FA-, and GBFS-blended cements.

The replacement ratio of binary and triple composition blended cements were chosen as 20% and 30%, depending on the compressive strength test results of single composition blended cements, given in Table 2. Compressive strength test results of the binary and triple composition blended cements are given in Table 3. The test results showed similar behavior as single composition blended cements at early ages. However, 28 and 180 days compressive

strengths of the second-group blended cements were found to be better, especially for Z- and GBFS-blended cements.

3.3. ASR resistance

ASTM C 1260 classifies aggregates with 14-day expansions greater than 0.2% as reactive, and those with expansions between 0.1% and 0.2% as potentially reactive [16]. Although ASTM C 1260 was originally designed for quickly identifying the reactive aggregates, it has been shown to be effective in determining the ability of supplementary cementing materials to mitigate ASR-related expansion [5]. The ASR experiments were carried out on for seven

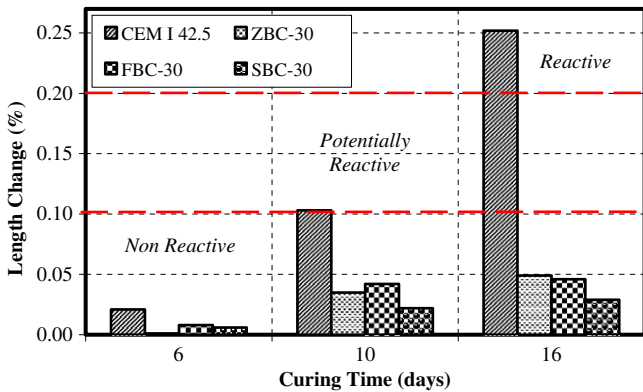


Fig. 4. The ASR length change of first group mortar bar specimens.

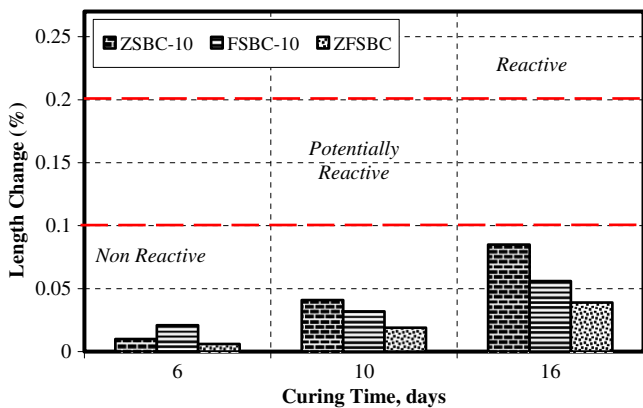


Fig. 5. The ASR length change of second group mortar bar specimens.

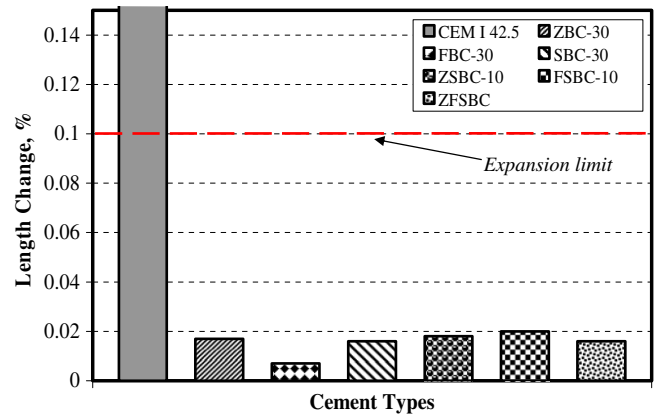


Fig. 6. The length change of mortar bar specimens against sulfate attack.

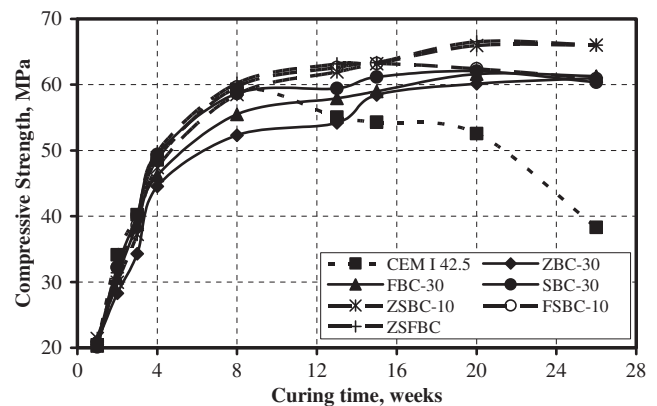


Fig. 7. Compressive strength variation of sulfate-resistance test specimens.

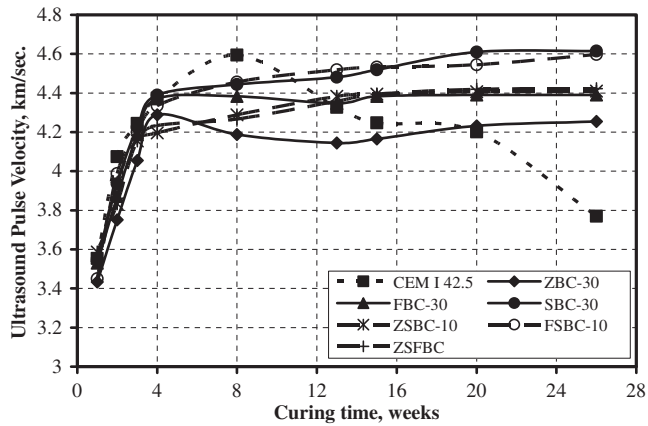


Fig. 8. UPV variation of sulfate-resistance test specimens.

different types of blended cements. The chemical compositions of the blended cements obtained from XRF tests are given in Table 4. From Table 4, it can be observed that the equivalent alkali content (EAC) of the blended cements are lower than reference cement. EAC plays a significant role in ASR expansion.

The ASR expansion test results of the first-group single composition blended cements for 30% replacement ratio are given in Fig. 4. It can be clearly observed that the reference CEM I 42.5 blended cement has risen above the 0.2% expansion limit (0.252) at the end of the 16-day specimen age. From Table 4, it can be noted that the EAC ratio of the reference CEM I 42.5 cement

(1.19) is the highest. Furthermore, it can be observed that at the end of the curing regime, FBC-30-, ZBC-30-, and SBC-30-blended cements are below the *non-reactive* boundary. The best performance was obtained with 30% GBFS-blended SBC-30 cement with 0.029% expansion ratio. The ASR crack formation on the surface of the CEM I 42.5 reference specimen could be seen clearly with naked eye. The cracks radiate from the interior of the aggregate particle and in the ambient cement paste.

The second-group blended cements' ASR expansion results are given in Fig. 5. As seen from Fig. 5, all types of blended cements' expansion ratios are below the expansion limit as defined in ASTM C 1260. The highest expansion was observed for ZSBC-10 (10% Z and 10% GBFS)-blended cement with 0.085 expansion ratio. The increased amount of C–S–H gels in the composite due to the reaction between calcium hydroxide and pozzolanic mineral additives in the blended cement compositions decreased the ASR gel formation of cement-based composite materials. The pozzolanic reaction and decreased EAC of the blended cement increased the durability of the concrete against ASR.

### 3.4. Sulfate resistance

Volume expansion of mortar bars was measured with 0.001-mm sensitive comparator for 6 months in accordance with ASTM C 1012 code. According to ASTM C 1157, the expansion limits of hydraulic cements were 0.10% and 0.05% at 26 weeks, considered as moderate sulfate resistant and high sulfate resistant, respectively [20]. Furthermore, 0.10% expansion limit was suggested for high sulfate resistant cements. The volume expansion of different

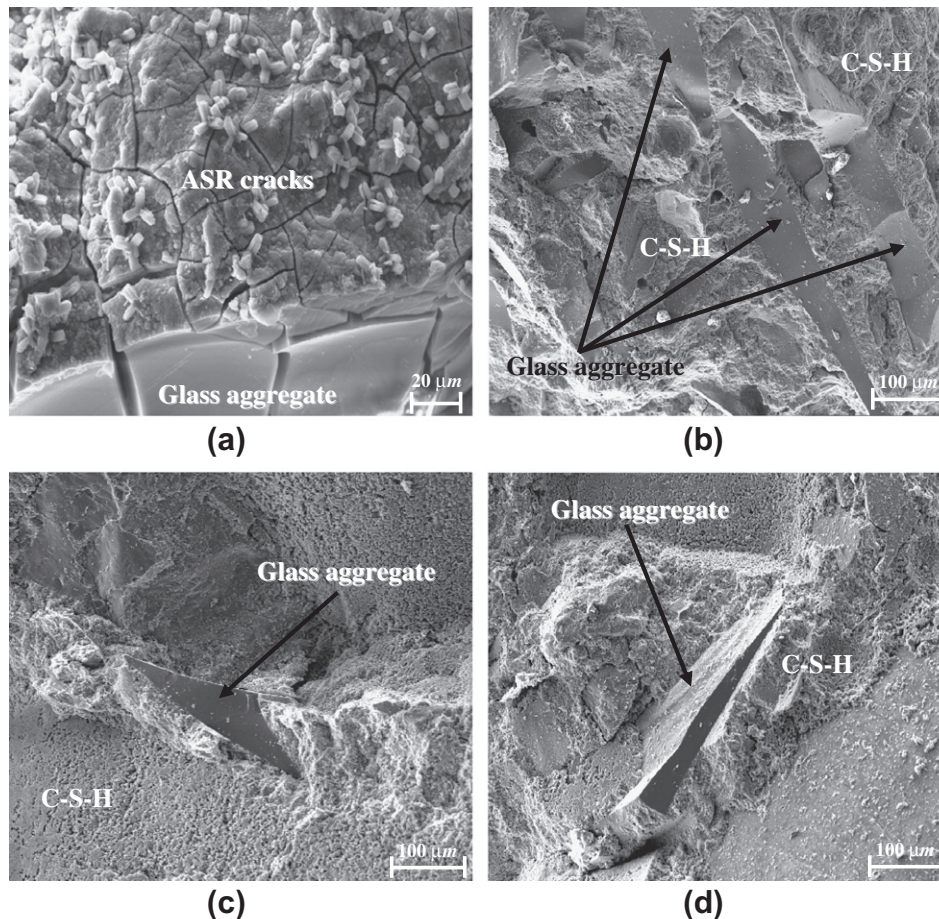


Fig. 9. Microstructure of ASR resistance test specimens. (a) CEM I 42.5; (b) ZBC-30; (c) FBC-30; (d) SBC-30.

cement mortars immersed in 10%  $\text{Na}_2\text{SO}_4$  solution for 26 weeks is given in Fig. 6. From Fig. 6, it can be observed that the reference mortar specimen produced with CEM I 42.5 reaches 0.518% above the 0.10% expansion limit after 26 weeks of sulfate exposure period. However, mortar bar expansion of ZBC-30- and FBC-30-blended cements replacement ratios were determined as 0.017% and 0.007%, respectively, below the reference line, as shown in Fig. 6. On the other hand, binary and triple composition blended cements expansion ratio were varied around 0.02%. These results are lower than the reference CEM I 42.5 ordinary Portland cement. According to these results, Z-, FA-, and GBFS-blended cements are more durable than ordinary Portland cement, under aggressive sulfate environments. It also appears that as the proportion of the replacement of clinker by pozzolanic material increases, the sulfate resistance of the mixture also increases. This conclusion, which is in accordance with other research results, indicates that the decrease in the  $\text{C}_3\text{A}$  content of the mixture, in combination with the reduction of large pores caused by the pozzolanic reaction, are more critical than the total porosity alone (which increases as the w/c ratio also increases) when sulfate resistance is of primary interest [21].

The mechanical behavior of different cement mortars during the sulfate test was investigated with compressive strength test results. As observed from Fig. 7, the compressive strength of CEM I 42.5 cement increased up to 59 MPa more rapidly than other cements at early ages. This increase should be attributed to the supplementary ettringite formation in the C-S-H structure of the composite. However, at the end of 8 weeks, this trend changed and strength reduction occurred with the expansion of ettringite

salt in the composite structure. On the other hand, the compressive strength of ZSBC-10 and ZSFBC cement mortars were increased by approximately 66 MPa at the end of the experimental study. Compressive strength test results show a good agreement with the volume expansion of cement mortars.

Ultrasonic methods are generally used for analyzing the porous structure, mechanical strength of the concrete, and to detect internal defects (voids, cracks, delaminations, etc.) [22]. Mortar specimens were subjected to UPV test to determine the crack formation of the composite material. As observed from Fig. 8, the UPV values of mortars increased with the curing time. However, the UPV value of CEM I 42.5 specimen was reduced after 8 weeks of exposure time. This significant reduction showed that the increasing volume expansion of the composite structure was the cause of the initial crack formation. Higher  $\text{C}_3\text{A}$  content of ordinary Portland cement was found to cause rapid ettringite formation in the composite structure when compared with other types of cements. On the other hand, the UPV values of all the produced blended cements were increased purposefully with the pozzolanic reaction between mineral additives and calcium hydroxide.

### 3.5. Microstructural investigation

At the end of the curing regime of ASR and sulfate-resistance tests, the microstructure of the blended cement mortar bar specimens were investigated by SEM analysis. The results of the ASR specimens are shown in Fig. 9. The morphology of CEM I 42.5 (Fig. 9a) suggests the high expansion of the mortar bar specimen due to the ASR gel formation near the reactive glass aggregate.

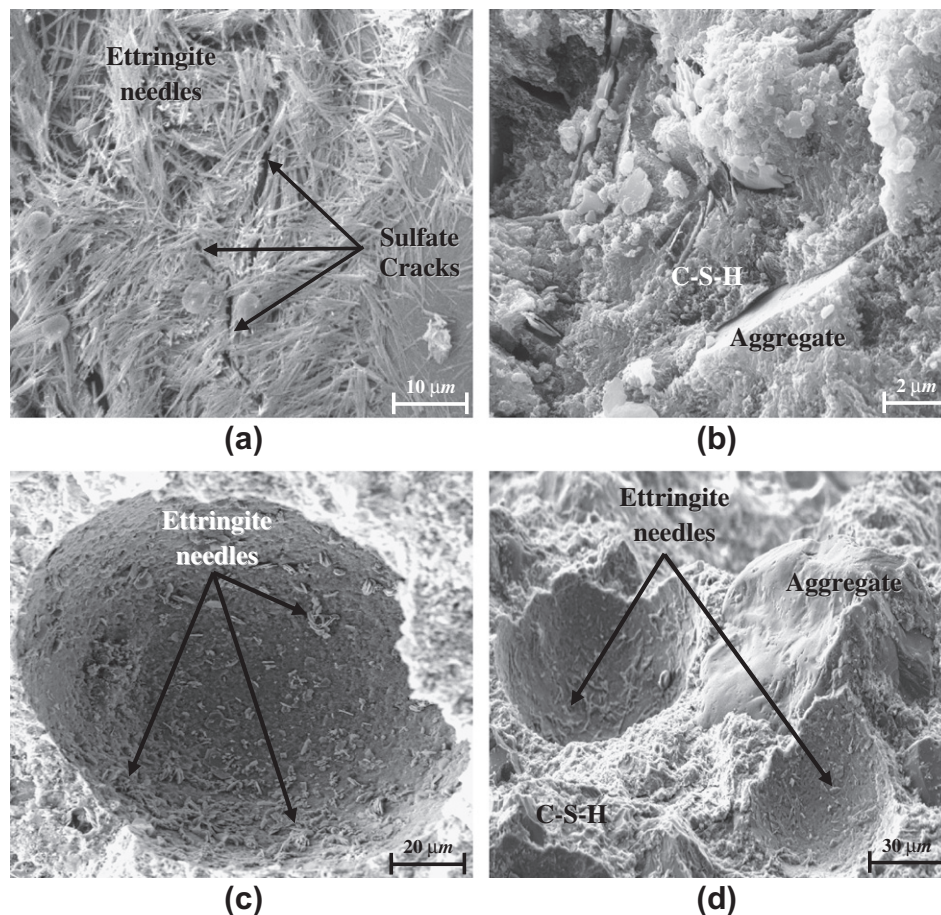


Fig. 10. Microstructure of sulfate-resistance test specimens. (a) CEM I 42.5; (b) ZBC-30; (c) FBC-30; (d) SBC-30.

Furthermore, the ASR crack formation could be seen clearly, which caused strength loss and volume stability of the composite. However, the microstructure of ZBC-30-, FBC-30-, and SBC-30-blended cements (Fig. 9b–d) showed no significant gel and crack formation. In addition, more dense C–S–H structure was detected for the blended cements consisting of Z, FA, and GBFS.

The microstructure of the sulfate-resistance test specimens are shown in Fig. 10. Ettringite formation is found to be the main cause of sulfate deterioration. Ettringite formation in the CEM I 42.5 mortar specimen (Fig. 10a) appears as long needles with small diameter. These needles expand in the presence of water and form cracks in the composite. This crack formation reduces the physical and mechanical properties of the specimen. However, ettringite formation in ZBC-30 (Fig. 10b) cannot be clearly seen as ordinary CEM I 42.5 specimen. For the case of FA- and GBFS-blended cements (Fig. 10c and d), ettringite formation is observed at the depth of the air voids for both the composites. However, these rare ettringite formations do not lead to any crack formation, as shown in Fig. 10a.

#### 4. Conclusions

The following conclusions can be summarized based on the experimental results in this study:

- The early-age strength development of GBFS-blended cement shows better performance than Z- and FA-blended cements. However, 180-day long-term compressive strength of all the produced blended cements are found to be higher than the reference CEM I 42.5 cement by up to 30% replacement ratio.
  - According to the expansion results, the ASR performance of blended cements are better than ordinary Portland cement. Zeolite, FA, and GBFS reduce the ASR gel formation in the microstructure of the composite. GBFS showed best performance against ASR tests.
  - Sulfate resistance of concrete is related to ettringite, gypsum, and thaumasite formation in the composite. As observed from the test results, Z-, FA-, and GBFS-blended cements protect the composite material against sulfate attack. Ettringite formation in the blended cement specimens are reduced than the reference ordinary Portland cement.
  - The strength and UPV loss of CEM I 42.5 reference specimen against sulfate attack at the end of the 26 weeks curing period were found as 132% and 164% respectively. However, no significant strength loss was determined for blended cements in the light of the test results.
- According to experimental test results the reduced presence of calcium hydroxide in the cement-based composites with pozzolanic reaction is found to increase the durability of the material against aggressive environments.

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