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Eco-friendly High-Strength Refractory Concrete Containing Calcium Alumina Cement by Reusing Granite Waste as Aggregate

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Abstract

Besides preventing valuable natural resources from going to waste, using stone waste from stone processing plants in concrete helps reduce environmental pollution and, therefore, offers a convenient route to sustainable development. The present study aims to use granite waste (GW) in high-strength refractory concrete. Sixteen high-strength refractory concrete mixes, including two water-to-binder ratios (W/B = 0.17 and 0.2), two silica-fume-to-binder ratios (SF/B = 0.15 and 0.2), two binder contents (B = 1200 and 1400 kg/m^3), and two replacement ratios of silica sand by granite waste (GW/Agg = 0 and 50%) were designed and prepared with high-alumina cement (HAC). The concrete specimens were exposed to 1200 ℃. Compressive and flexural strength and scanning electron microscopy (SEM) tests were performed on specimens of concrete mixes before and after heating. It was found that in specimens with high binder content (1400 kg/m^3), replacing 50% silica sand with GW (GW/Agg = 50%) in refractory concrete improves compressive and flexural strengths by 3–15 and 4–24% before heating, respectively. It was also shown that using GW to replace silica aggregates in concrete specimens with a 1200 kg/m^3 binder content not only did not undermine, but also improved the compressive and flexural strengths of refractory concrete after heating by 20–78% and 15–60%, respectively, as a result of sintering. Meanwhile, in the case of the concrete with 1400 kg/m^3 binder content, adding GW exacerbated its loss of compressive and flexural strengths after heating due to little or lack of sintering.

Keywords: sustainable development, granite wastes, high-strength refractory concrete, compressive strength, flexural strength

1 Introduction

The notion of sustainable development was introduced in response to negative environmental and social consequences of one-dimensional economic development emerging at the dawn of the industrial revolution and change in humankind attitude toward growth and progress. This concept attempts to shed new light on the development and prevent previous mistakes from being repeated by promoting comprehensive and balanced development. Sustainable development is a process that pictures for societies the image of a desirable future in which living conditions and use of resources are maintained to meet human needs without harming the integrity, elegance, or stability of vital systems and without compromising the ability of future generations to meet their needs (Sjöström, 1999). Protecting the environment, as a primary element of sustainable development, must be part of the plan in technology and industry selection and the relevant policies.

The increasing use of minerals and the extraction of resources call for the construction industry to adopt environmentally friendly materials. Second only to water, concrete is the most widely used construction material. Concrete is known as one of the most widely used

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building materials after water. Since 2005, annual concrete production has reached nearly six billion tons or one ton per capita. That figure indicates the copious amounts of natural resources consumed by the concrete industry. Accordingly, using industrial waste for making concrete is a suitable way to prevent environmental degradation and avoid natural resources from going to waste (Al-Zboon and Al-Zou'by, 2015).

Statistics on the production of decorative sedimentary stones in Iran, India, Italy, Spain, and Egypt are indicative of a flourishing industry (Aliabdo et al., 2014). According to the data collected by the Industrial Development and Renovation Organization of Iran, around 6000 stone processing plants operate in the country. Overall, these plants produce in excess of 9 million tons of waste annually. Nearly 40% of these plants produce granite stone. In Mahmoudabad Industrial Park in Isfahan, Iran, seventy granite processing plants are active. In the granite production process, 30% of each slab turns into stone sludge. The wastes are often loaded into trucks to be carried away and disposed of in nature. This practice, on the one hand, is detrimental to the environment, and on the other hand, inflicts additional transport costs to stone processing plants (Savadkoohi & Reisi, 2020). Making use of these wastes protects the environment, which is a prerequisite to sustainable development in the present time. Accordingly, extensive studies have addressed the use of wastes, particularly granite waste (GW), in the construction industry especially in concrete. Some researchers have studied the effects of substituting aggregates with GW on the workability of conventional concrete (Falade, 1999; Mármol et al., 2010; Singh et al., 2016a, 2016b, 2016c). It was found that concrete workability is compromised by replacing aggregates with GW. These reports contradict the view held by others who claim substituting aggregates with Crushed Granite Waste (CGW) in the concrete improves its workability (Adigun & Eng, 2013; Felixkala & Sethuraman, 2013; Manasseh, 2010; Raghavendra et al., 2015). Some researchers carried out studies to determine the optimal replacement ratio of aggregates by GW in normal concrete (Allam et al., 2014; Arivumangai & Felixkala, 2014; Chiranjeevi Reddy et al., 2015; Elmoaty, 2013; Garas et al., 2014; Ghannam et al., 2016; Mashaly et al., 2018; Sharma et al., 2017; Singh et al., 2015). Studies report the optimal replacement ratio to maximize compressive, flexural, and tensile strengths and minimize water absorption to be 15–55%, 7.5–55%, 7.5–30%, and 15–55%, respectively (Arulraj et al., 2013; Divakar et al., 2012; Rao et al., 2012a; Rao et al., 2012b; Singh et al., 2017; Vijayalakshmi & Sekar, 2013). The consequences of adding GW to mortar to replace cement have also been studied (Sadek et al., 2016; Serelis et al., 2018). The results are suggestive of reduction in compressive strength of mortar as a result of the inclusion of GW. Furthermore, the decline of compressive strength after the replacement of cement with GW was shown to be negligible. Some studies considered the effects of replacing fine aggregates with Granite Waste Aggregates (GWA) in self-compacting concrete (SCC). It was shown that using 20% GWA instead of fine aggregates in SCC maximizes the compressive and flexural strengths. Serelis, et al. studied the replacement of cement with GWA in lightweight concrete (Serelis et al., 2018). The results were indicative of reduced concrete density, compressive strength, and flexural strength. Savadkoohi and Reisi studied how GW influenced the mechanical properties of reactive powder concrete (RPC) (Savadkoohi & Reisi, 2020). It was shown that the mechanical and physical properties of RPC could be improved by increasing the replacement ratio of silica sand by GW up to 30%, as the compressive and flexural strengths were enhanced by 20–78% and 15–60%, respectively, whereas water absorption was reduced by 15–78%. Since the GW was finer than silica sand particles, raising GW/Agg from 30 to 40% increased the total GW surface area, undermining the concrete quality due to the lack of sufficient cement paste to fully cover the aggregates. In most concrete mixes, the physical and mechanical properties of the concrete with GW/Agg=40% were higher than the concrete without added GW (Savadkoohi & Reisi, 2020).

2 Refractory Concrete
Some references report 1000 °C to be the border between the thermal and melting resistance, while others have reported it to be 1500 °C (Newman & Choo, 2003c). As a general definition, refractory concrete is a type of concrete made of calcium aluminate cement (CAC) for high-temperature applications. Using CAC in concrete dates back to WWI, but this type of cement was first industrially produced by Bied in 1908 in the French company Lafarge (Newman & Choo, 2003a). The primary objective in producing this type of cement was to prepare sulfate-resistant concrete. Over time, further research on this type of cement revealed more of its qualities including its refractory property (Falade, 1999; Newman & Choo, 2003b).

Exposure of Portland cement concrete (PCC) to high temperatures results in drastic microstructural changes, and hence, compromises its strength. PCC loses nearly half of its strength at 600 °C and most of it at 800 °C (Newman & Choo, 2003c). Failure of PCC at high temperatures can be attributed to the following phenomena (Newman & Choo, 2003b):

1- Expansion and shrinkage differences between aggregates and cement paste at high temperatures, promoting crack growth.
2- Damage to the concrete matrix due to the decomposition of portlandite ($Ca(OH)_2$) and calcium silicate hydrate (C–S–H).
3- Creep inside the concrete due to the growth of voids as water bonds break by evaporation.
4- Pore pressure build-up by steam developing in the concrete, resulting in fine cracks and exfoliation at high temperatures.
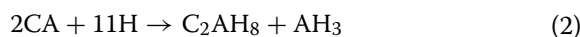5- Cracking due to the partial re-hydration of the dehydrated lime after cooling

As a general rule, in refractory concretes made with HAC, refractory properties depend on the alumina content and the type of aggregates (Newman & Choo, 2003b). Accordingly, the type of aggregates used in this type of concrete is different from that used in conventional ones. Most aggregates incorporated in the refractory concrete are either synthetic or made by natural heating processes. As is the case with cement, the melting point of aggregates also depends on their constituents. Given the variety of available refractory concretes and their applications today, temperature cannot be considered as the only factor determining the type of aggregates to be used in concrete: other factors include abrasion resistance, expansion and shrinkage properties, and acid resistance. Silica sand, granite, basalt, and synthetic calcium aluminate are examples of aggregates used in refractory concretes capable of withstanding temperatures up to 1710, 1260, 1200, and 1870 °C, respectively (Somayaji, 2011). Tufail et. al reported that concrete made with granite aggregate have higher mechanical at temperature up to 650 °C than concretes made with quartzite or limestone (Tufail et al., 2017).

The most notable properties of concretes made with HAC include (Neville & Brooks, 1987; Newman & Choo, 2003d): (1) High-temperature resistance (up to 2000 °C); (2) fast hardening (24 MPa in 5 h); (3) abrasion resistance and high durability; and (4) resistance to chemical attacks.

As mentioned earlier, several definitions have been proposed for refractory materials, such as cement and concrete. Accordingly, refractory concretes can be classified by the temperature range they can withstand into three general categories (Newman & Choo, 2003b):

1. Normal refractory concrete: 1580–1780 °C
2. Resistant refractory concrete: 1780–2000 °C
3. High-resistance refractory concrete: above 2000 °C

HAC concrete is cured with 15–27 °C water (Newman & Choo, 2003a, 2003c). HAC hydration promotes other chemical reactions including those expressed by Eqs. 1–3 forming unstable crystals. The size and type of crystals depend on the ambient temperature and humidity. For example, below 15 °C, Eq. (1) dominates, but curing at 15–27 °C is more suitable for the formation of Eqs. (2) and (3), the products of which are more stable and more compact than those of Eq. (1).

$$CA + 10H \rightarrow CAH_{10} \tag{1}$$

$$2CA + 11H \rightarrow C_2AH_8 + AH_3 \tag{2}$$

$$3CA + 12H \rightarrow C_3AH_6 + 2AH_3 \tag{3}$$
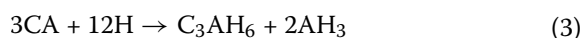
The crystals forming in these chemical reactions (C_2AH_8 and CAH_{10}) are all metastable and over time by achieving the energy required are transformed to C_3AH_6 and AH_3 crystals by Eq. (4) and (5). These compounds are the final stable products of HAC reaction with water at ambient temperature.
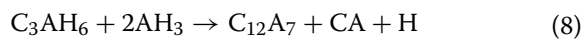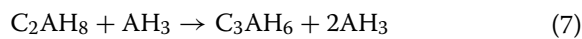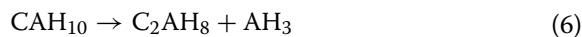
$$2CAH_{10} \rightarrow C_2AH_8 + AH_3 + 9H \tag{4}$$

$$3C_2AH_8 \rightarrow 2C_3AH_6 + AH_3 + 9H \tag{5}$$
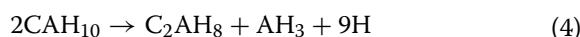
In each phase of transformation from CAH_{10} to C_3AH_6 and AH_3, the density of the newly formed crystals increases. Since the particle's density changes at constant concrete mass, the newly formed crystals are spaced further apart in each stage of phase transformation, increasing the concrete porosity.

When HAC is exposed to high temperature, its free moisture content and water in hydrated products is

Table 1 Physical and chemical specifications of the cement and silica fume

Component	Cement	Silica fume (SF)
CaO	40–36	1.5
SiO$_2$	8–3	90–95
C	–	0.8–3
Al$_2$O$_3$	42–36	1
Fe$_2$O$_3$	2–3.5	2
MgO	1	2
K$_2$O	–	0.2–0.5
SO$_3$	–	–
H$_2$O		0.01–0.4
TiO$_2$	< 0.5	
Total alkali	–	–
Specific surface area (m^2/kg)	–	15,000–30,000
Unit volume weight (kg/m^2)	-	310–350

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gradually eliminated. In general, weak bonds of water break as the temperature reaches 100 °C, and at 120 °C, CAH_{10} becomes dehydrated. In the following, C_2AH_8 and C_3AH_6 begin to decompose as temperature reaches 200 to 300 °C. $C_{12}A_7$ forms in higher temperature ranges (500–800 °C), and CA and C_2A begin to form beyond 1000 °C. Equations (6) to (9) express the chemical reactions that take place in this stage (Choo, 2003). CA and C_2A are the final crystals, formed in the concrete exposed to high temperatures and have ceramic structures and melting points of 1600 and 1750 °C, respectively (Newman & Choo, 2003c):

$$CAH_{10} \rightarrow C_2AH_8 + AH_3 \tag{6}$$

$$C_2AH_8 + AH_3 \rightarrow C_3AH_6 + 2AH_3 \tag{7}$$

$$C_3AH_6 + 2AH_3 \rightarrow C_{12}A_7 + CA + H \tag{8}$$

$$C_3AH_6 + 2AH_3 + A \rightarrow CA + H \tag{9}$$

The decline of the compressive strength of HAC after heating depends on the alumina content of cement and the temperature it was exposed to. With that said, 20–30% loss of compressive strength has been reported in the 1000–1200 °C range (Bareiro et al., 2018; Vejmelková et al., 2018).

3 Significance of Study

Due to its considerable SiO_2 content, GW produced in stone processing plants can withstand high temperatures, making it suitable to be used as aggregates in refractory concrete. Besides preventing natural resources from going to waste, this approach helps control the environmental pollution. In this light, the present study focused on using these wastes to prepare refractory HAC concrete. As GW particles are under 0.3 mm in size, the refractory concrete with GW aggregates requires high amounts of cement, making it a high-strength powder

Table 2 Grading of the aggregates

Sieve No.	Sieve size (mm)	silica sand (T60)	Granite Waste
30	0.6	100	100
40	0.42	89.5	94.1
50	0.3	53.5	88.3
70	0.21	18.6	77.4
100	0.15	4.1	50.1
170	0.09	0	29.5
200	0.075	0	9.6
400	0.038	0	0

Table 3 Physical and chemical specifications of the aggregates

Component	Standard sand (ASTM C146, 2004)	Used silica sand	Used granite waste (GW)
SiO_2	96–98.1	97–99	91.18
Fe_2O_3	0.2–0.7	0.2–0.6	1.9
Al_2O_3	0.51–1.63	0.4–1.7	0.22
CaO	0.4–0.7	0.07–0.2	0.53
Na_2O	0.03–0.8	0–0.1	0.08
K_2O	0.02–0.08	0.02–0.06	1.13
MgO	–	–	1.82
TiO_2	–	–	0.05
P_2O_5	–	–	0.04
MnO	–	–	0.11
SO_3	–	–	0.37
Cl	–	–	0.05 <
LOI	–	0.01–0.35	2.72

refractory concrete. High-strength powder refractory concrete due to incorporating HAC and aggregates containing silica and granite, can withstand temperatures of up to 1600 °C.

As mentioned, the present study aims to investigate the effect of incorporating GW on the compressive and flexural strengths and workability of high-strength powder refractory concrete. Several studies have addressed using GW in different types of concrete, including conventional concrete (Prokopski et al., 2020), self-compacting concrete (SCC) (Jain et al., 2020), and the reactive powder concrete (RPC) (Savadkoohi & Reisi, 2020). A review of the available literature shows that no previous research has studied using GW to make refractory concrete. The same review also indicates a dearth of publications on using other types of waste in refractory concrete (Abyzov, 2017; AlArab et al., 2020; Baradaran-Nasiri & Nematzadeh, 2017). Some of these works are discussed briefly in the following. Baradaran-Nasiri and Nematzadeh (2017) studied using refractory brick waste to make HAC refractory concrete (Baradaran-Nasiri & Nematzadeh, 2017). They reported a much higher strength for the concrete with HAC and refractory brick than a refractory concrete with regular aggregates at 800 °C. The results showed that the refractory brick aggregates did not improve the elastic modulus of concrete. The results also indicated the specimens showed a similar weight loss to the concrete without waste. Abyzov used waste phosphate and alumina as binder for making refractory foamed concrete (Abyzov, 2017). They concluded that concretes made with waste-alumina and phosphate binders could withstand temperatures in the 1450–1650 °C range. It was also stated that the refractory concrete

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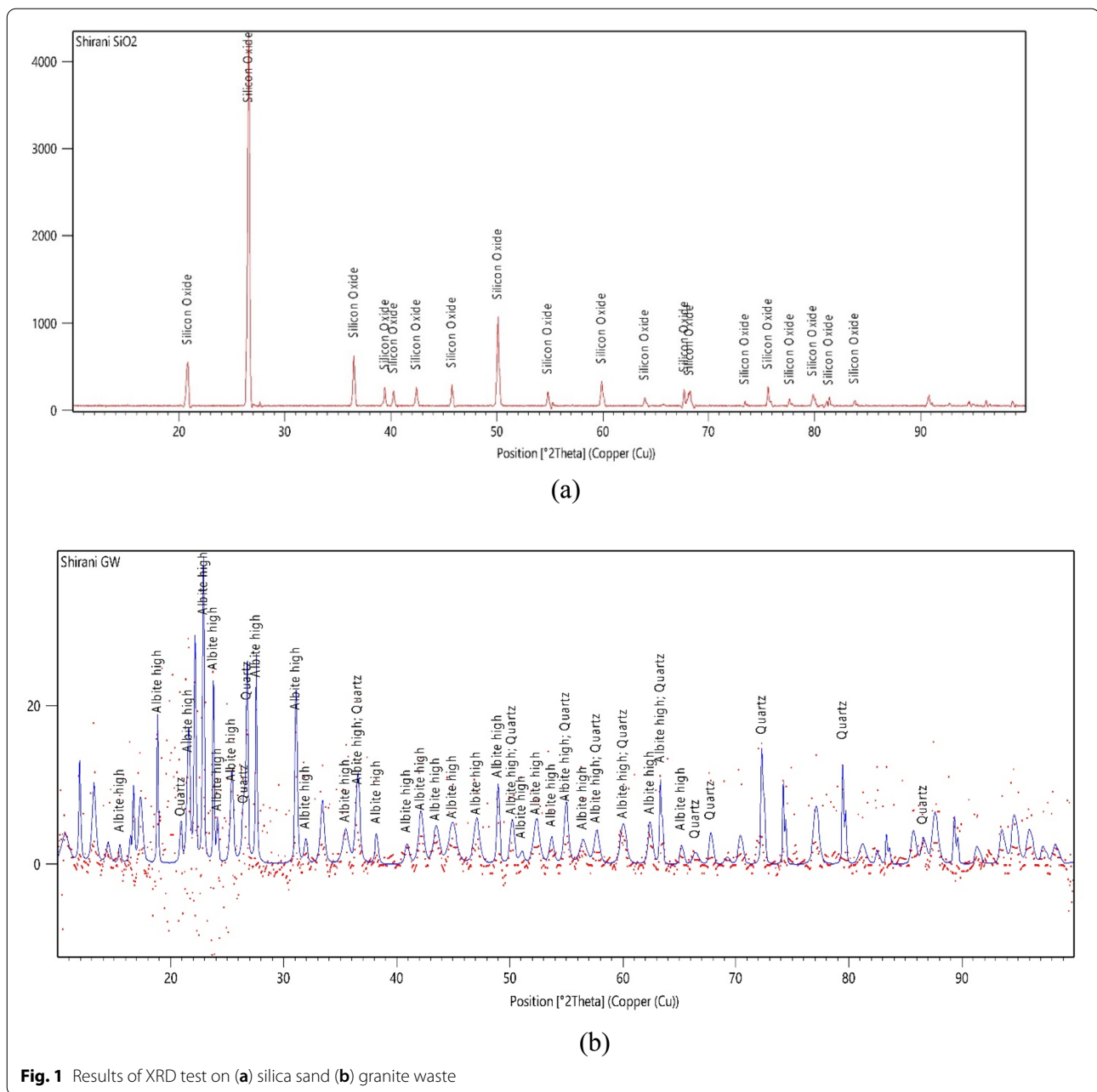
Fig. 1 Results of XRD test on (**a**) silica sand (**b**) granite waste

made by this method has no detrimental impact on the environment while maintaining the same level of residual strength as that of a typical refractory cellular concrete. Dockman and Mladenovič studied using steel sludge to make refractory concrete (Ducman & Mladenovič, 2011). It was shown through XRF analysis that the iron waste undergoes a phase transformation at 700–800 °C. This irreversible phase transformation enables the concrete to be used in the 800–1000 °C temperature range due to the stability of the wastes at these temperatures. Alarab et al. showed that using ceramic wastes in concrete can improve thermal properties of concrete (AlArab et al., 2020).

## 4 Experimental Study
4.1 Materials
The following materials were used in the experiments.

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Table 4 Mix design proportioning

Mixture No	SF/B	W/B	Amount of ingredients (kg/m^3)				
			C	SF	B	W	Agg
M1	0.15	0.17	1190	210	1400	243	685
M2	0.15	0.2	1190	210	1400	284	606
M3	0.2	0.17	1120	280	1400	243	694
M4	0.2	0.2	1120	280	1400	284	581
M5	0.15	0.17	1020	240	1200	211	999
M6	0.15	0.2	1020	240	1200	246	901
M7	0.2	0.17	960	210	1200	211	977
M8	0.2	0.2	960	210	1200	246	879

Cement As discussed in earlier sections, the refractory properties depend on the presence of low-melting-point materials, such as SiO_2, Fe_2O_3, and CaO in the HAC. Among all different types of refractory cement, gray cement with 40% alumina is the usual candidate for making refractory materials withstanding up to 1200 °C. In the present study, HAC with a 40% alumina content (product of Iran Refractory Cements Co.) was used. Table 1 lists the physical and chemical properties of this cement.

Silica Fume An ASTM C1240-compliant silica fume produced by Iran Ferroalloy Industries Co. with 90–95% active silica was used as the pozzolanic and filler material (ASTM C, 1240, 2005). Given that the studied refractory concrete belongs to the powder concrete category and has a considerable content of cementitious materials, using silica fume with grains smaller than 1 μm fills the concrete more densely. In addition, according to the results obtained by Ding et al., The use of silica fume in alumina cement due to the chemical reaction of cement with SiO2 in silica fume, in addition to the formation of hydrated materials, such as CAH_{10}, C_2AH_8, C_3AH_6 and AH_3, produces a substance called Gehlenite and Stratlingite with chemical bonds of Ca_2Al [AlSiO7] and (C2ASH8 Ca2Al2O3SiO2.8H2O), respectively. (Ding et al., 1995):

$$SiO_2 + CaOAl_2O_3 + H_2O \rightarrow C_2ASH_8 \qquad (10)$$
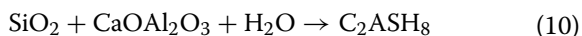
Having similar properties to C–S–H in Portland cement, C_2ASH_8 improves the compressive strength of concrete. Moreover, as mentioned before production of C_3AH_6 from HAC hydration increases the porosity of the HAC concrete; so adding silica fume to the mixture decreases the amount of C_3AH_6 and produces C_3ASH_8 which leads to the improvement in the compressive strength of concrete specimens before heating (Bareiro et al., 2018; Hidalgo et al., 2009). Table 1 lists the physical
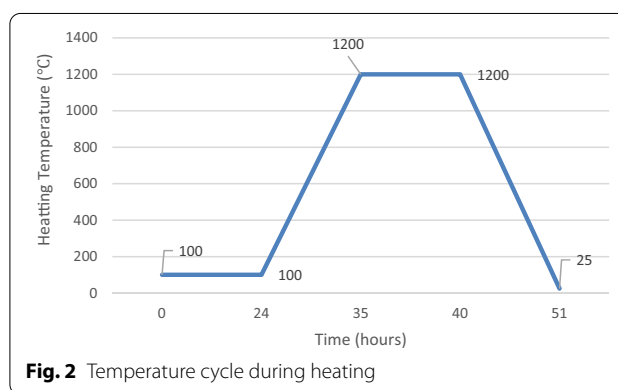

Fig. 2 Temperature cycle during heating

and chemical properties of the silica fume used in these studies.

Superplasticizer The polycarboxylate–ether-based superplasticizer Structure 335 (product of FOSROC) was used to improve the fluidity of the high-strength refractory concrete. The brown, liquid superplasticizer complies with the ASTM C494 types A and G standards and has a specific gravity of 1.1.

Silica Sand Chirok T60 silica sand with 0.5% water absorption, a specific gravity of 2.7, and a melting point of 1650–1700 °C was incorporated as aggregates into high-strength refractory concrete mixes. Tables 2 and 3 present physical and chemical properties and the grading of the silica sand, respectively. In Fig. 1a, XRD test result of silica sand is also illustrated.

Granite Waste The GW used for making the high-strength refractory concrete was retrieved from filter presses at stone processing facilities in Mahmudabad Industrial Park, Isfahan, Iran. First, the collected granite sludge was dried in a 100 °C oven for 24 h. The aggregates were then moved to a Los Angeles abrasion test machine to separate the agglomerated dried particles. The powdered dried waste was then incorporated into the mix. XRD test, Grading, water absorption, and XRF tests were
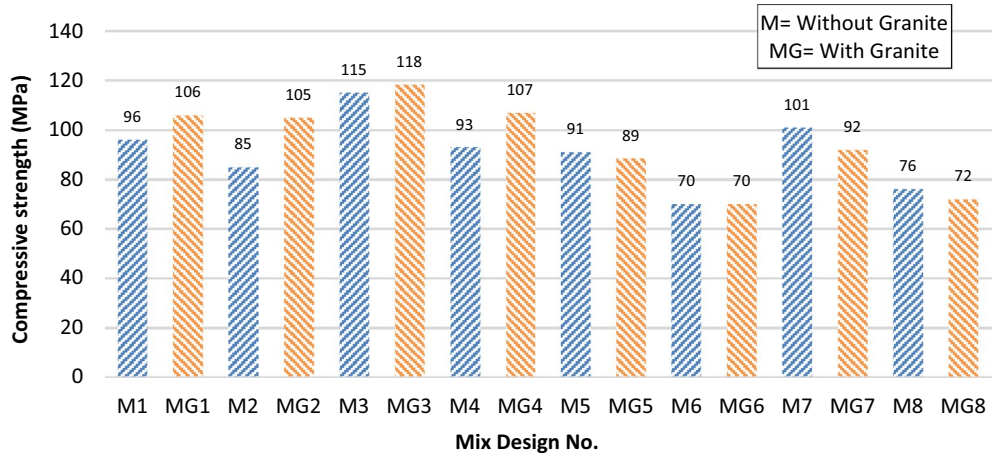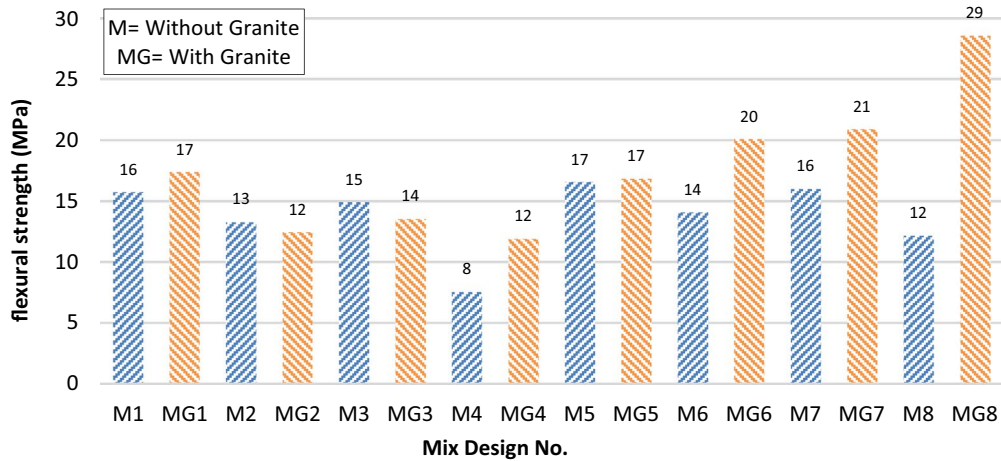
Fig. 3 Compressive strength of mixes with and without GW before heating
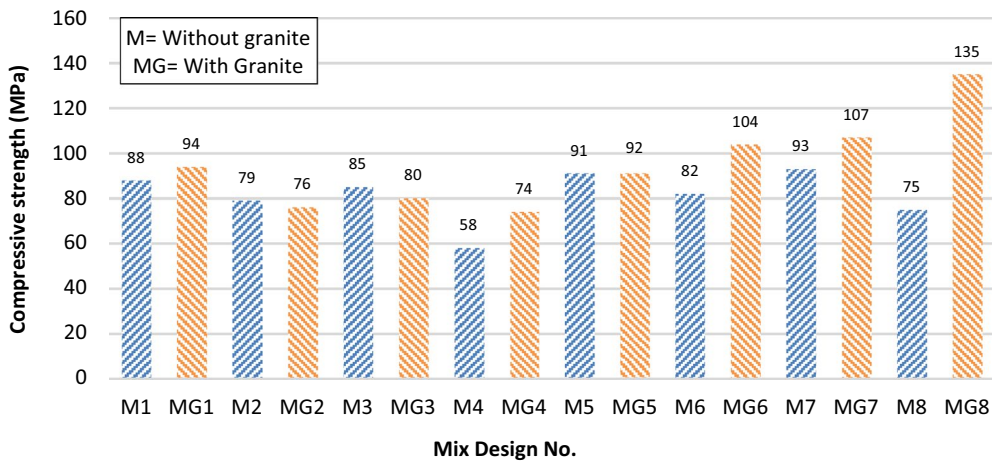
Fig. 4 Compressive strength of mixes with and without GW after heating

Fig. 5 Flexural strength of mixes with and without GW before heating

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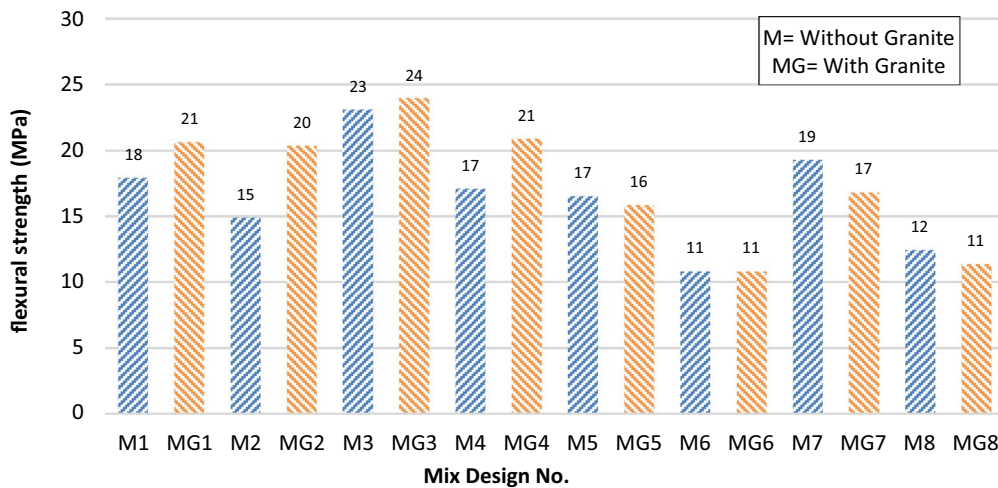
**Fig. 6** Flexural strength of mixes with and without GW after heating

carried out for the GW, and the results are presented in Fig. 1b, Tables 2 and 3. As can be seen in Fig. 1, the granite waste aggregate contains some albite. As mentioned in various references, albite is a type of aggregate from the feldspar family that is naturally extracted from albite ores or by flotation from rocks, such as granite (Harada & Hagiwara, 1984)

4.2 Mix Designs
As discussed earlier, the aim of this study is to study the effect of GW on the mechanical properties of high-strength refractory concrete before and after heating to 1200 °C. Accordingly, eight mix designs (M1 to M8) were prepared considering two binder ratios (B = 1400 and 1200 kg/m^3), two silica-fume-to-binder ratios (SF/B = 0.15 and 0.2), and two water-to-binder ratios (W/B = 0.17 and 0.2). Table 4 summarizes the mix design proportions. Each of the reference mixes was remade by substituting 50% silica sand with GW to determine the effects of using GW in high-strength refractory concrete (MG1 to MG8). Overall, sixteen high-strength refractory concrete mixes were designed and prepared.

The workability of this powder refractory concrete is particularly important. The concrete comprises considerable amounts of binder and fine aggregates and can lose its workability fast. Therefore, it must
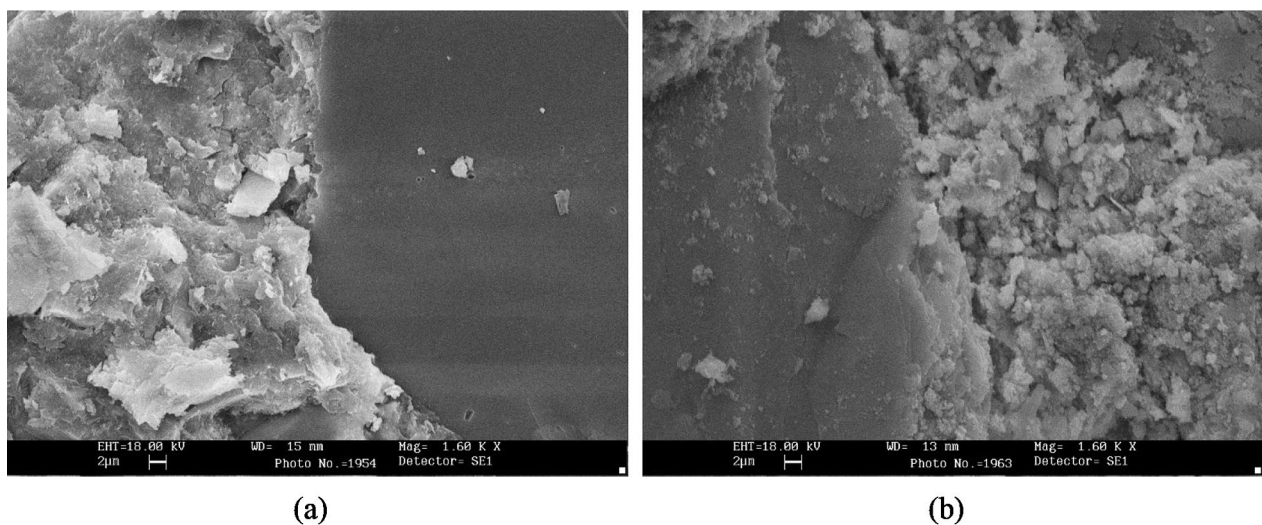
Fig. 7 Transition zone of mixes **a** with 1400 kg/m^3 and **b** 1200 kg/m^3 binder contents

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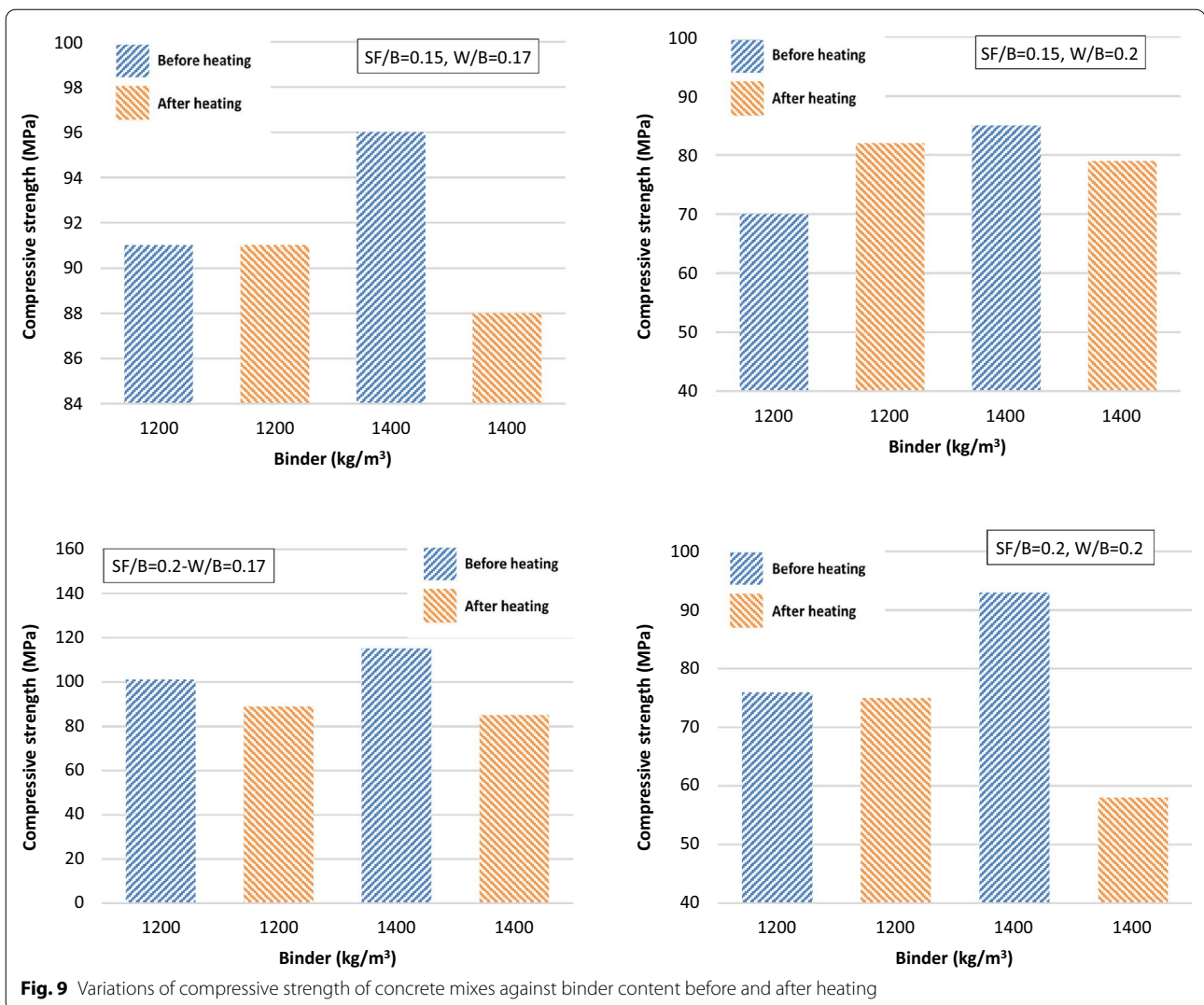
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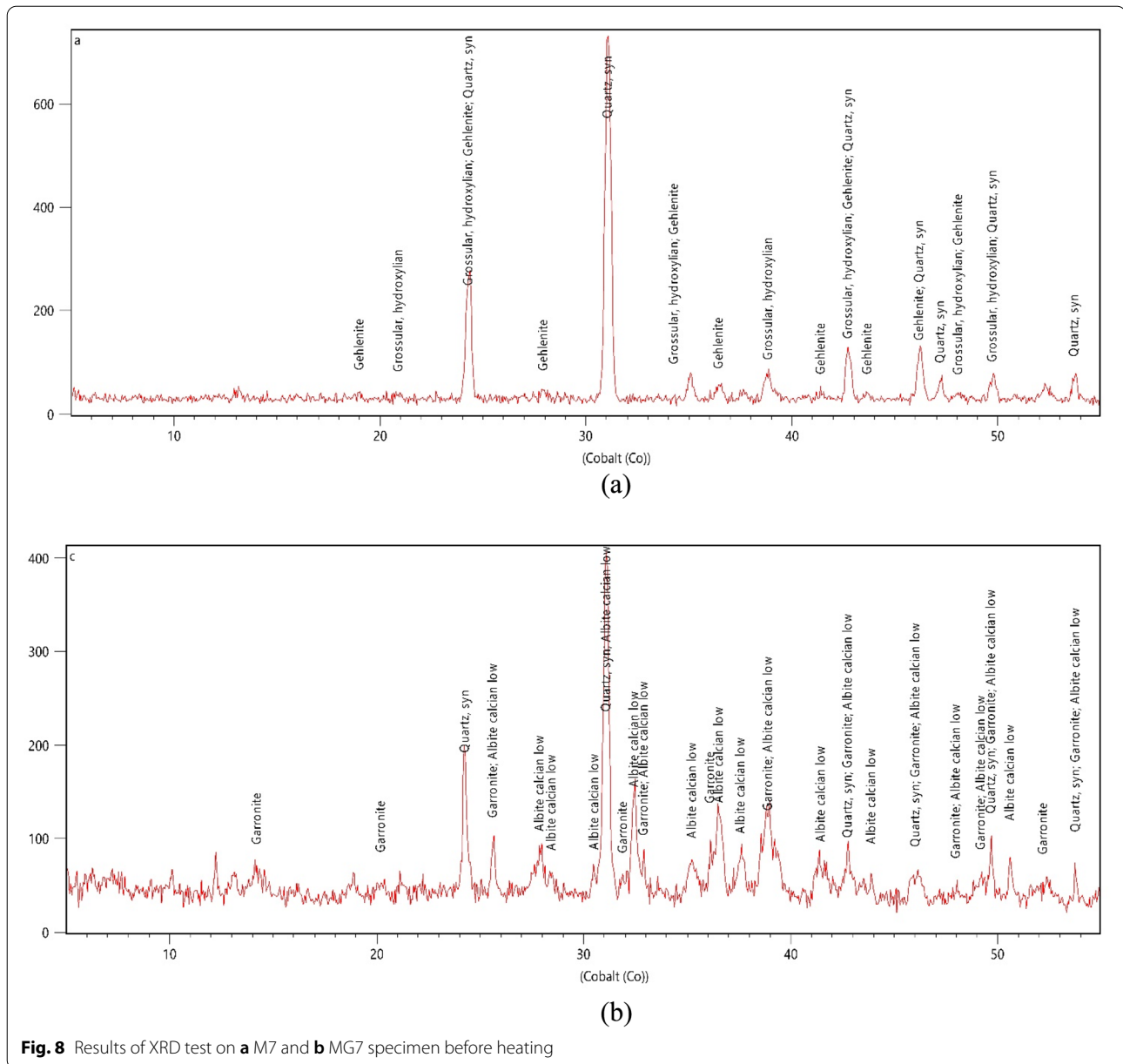
Fig. 8 Results of XRD test on **a** M7 and **b** MG7 specimen before heating

be reasonably fluid during preparation. Moreover, all specimens must be similar in terms of fluidity to allow for comparison. Therefore, similarly to some previous studies, the fluidity was determined by the mini-slump flow test according to the ASTM C1437 (ASTM C, 1437, 2001) and ASTM C230 (ASTM C230/C 230 M, 2004). Based on this standard, first, a 50-mm-tall truncated cone with top and bottom diameters of 70 and 100 mm was placed on the flow table. The cone was then filled with fresh concrete and then lifted abruptly. The table was then tapped 25 times. Finally, the spread diameter of the concrete was measured. The spread

diameter of all studied concrete specimens was maintained at 200 ± 10 mm by adjusting the superplasticizer content.

4.3 Preparing the Specimens

Previous studies on powder concretes showed powder concrete must be prepared using high-speed mixers (Hiremath & Yaragal, 2017a, 2017b). It has been reported that using a high-speed mixer will reduce concrete porosity and improve its quality. These studies include

Fig. 9 Variations of compressive strength of concrete mixes against binder content before and after heating

the works of Hirmat and Yargul who reported the suitable mixing speed and duration for powder concrete to be 100 rpm and 15 min, respectively. The mixer was used in the present study for mixing has maximum speed of 360 rpm.

The following mixing method was employed in the present study based on experimentation and other results reported in the literature.

- Dry mixing of cement, silica fume, aggregates, and GW at 120 rpm for 3 min;
- Adding half the measurements of water and super-plasticizer and further mixing at 120 rpm for 5 min;
- Adding the remainder of water and superplasticizer and proceeding to mix at 360 rpm for 5 min.

After mixing, the different mixes were tested on the flow table and then molded. The specimens were then placed on a plate vibrator to maximize its compaction. Six 100×100×100 mm cubes were prepared from each concrete mix for compressive strength testing and six 40×40×160 mm prisms for flexural strength testing before and after heating. In total, 192 (=12 × 16) specimens were prepared.

After molding, the specimens covered with a damp cloth to prevent loss of moisture and were left in the mold for 24 h. They were then removed from the mold and placed in a 22 °C water tank for 28 days to cure and transform to the stable phase. After curing, the specimens of each mix were removed from the tank and left to dry before sorting into two groups. The first group

Fig. 10 Variations of flexural strength of concrete mixes against binder content before and after heating
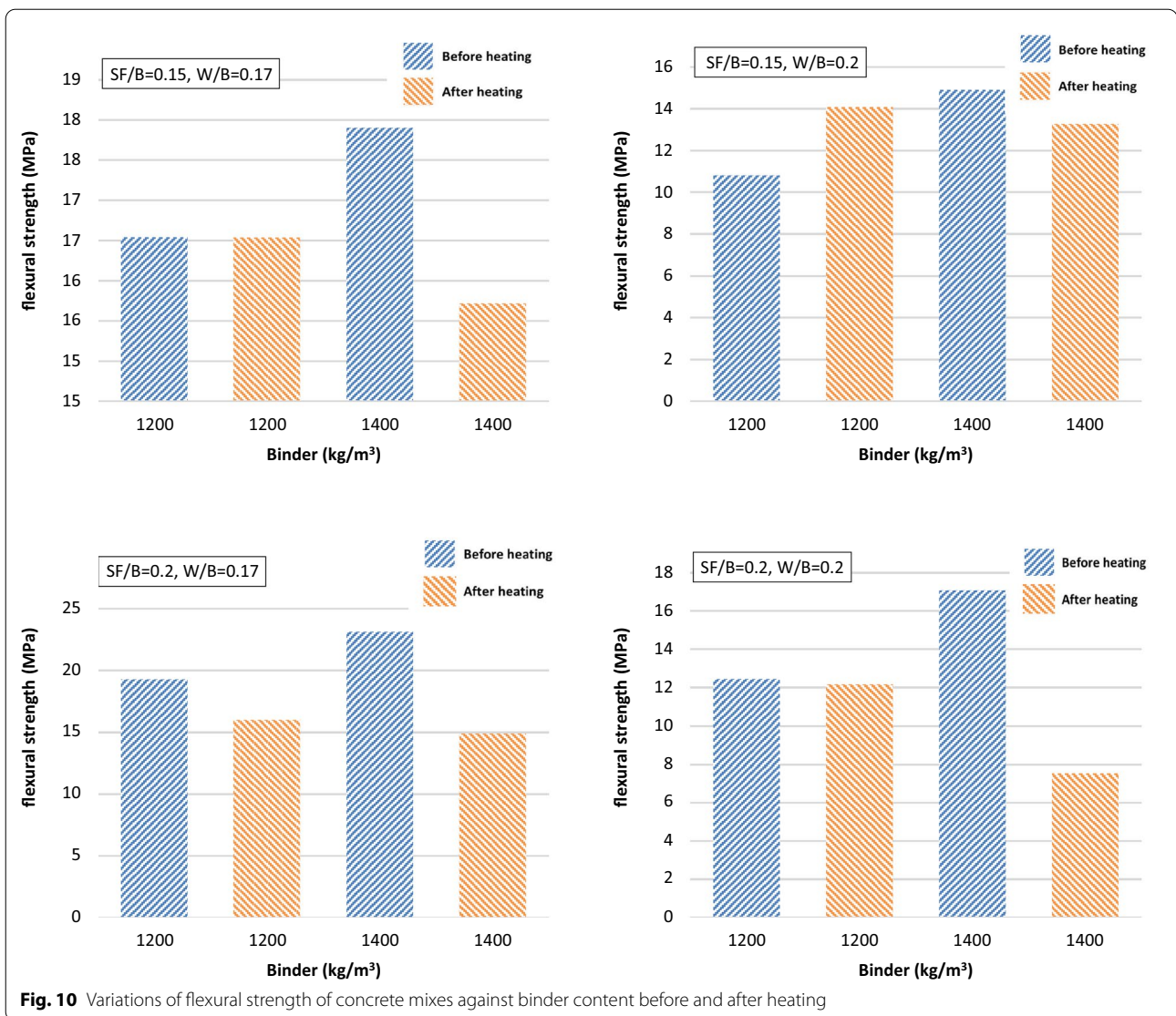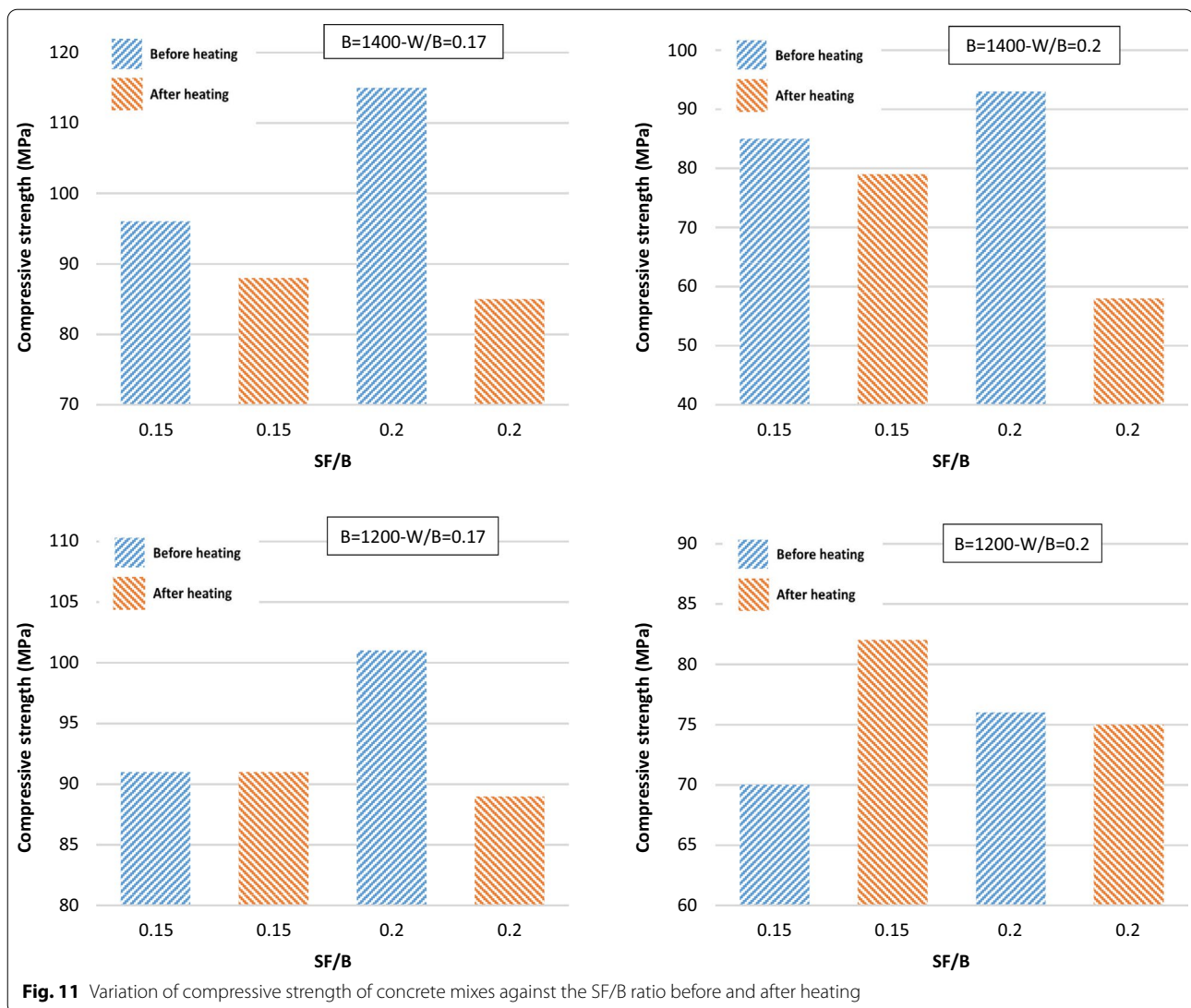
was used in compressive and flexural strength tests subsequently after drying, whereas the second group of specimens was placed in a 100 °C oven for 24 h to dry thoroughly. These were then heated in a 1200 °C furnace. Fig. 2 shows the temperature variations in the furnace. The process of temperature changes inside the furnace is in accordance with ASTM C865 standard and according to Fig. 2. According to this standard, the samples must be heated at a heating rate in the range of 55 to 380° C until reaching the target temperature, then heated to the target temperature for 5 h and cooled to a temperature reduction rate of less than 280° C per hour. In this paper, as shown in Fig. 2, the samples were heated at a rate of increase of 100° C per hour. Then,

they were kept at the target temperature (1200° C) for 5 h and cooled to a temperature of 107° C/h until they reached room temperature (ASTM C865, 2002).

After heating and cooling, the specimens were removed from the furnace for compressive and flexural strength tests.

5 Results

Compressive and flexural strength tests were carried out according to the ASTM C109 (ASTM C109, 2002) and ASTM C293 (ASTM C293, 2002). The compressive and flexural strengths were measured using a 2000 KN

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Fig. 11 Variation of compressive strength of concrete mixes against the SF/B ratio before and after heating

compression testing machine at the speed 0.25 MPa/s and a flexural testing machine. The compressive strength results are presented in Figs. 3 and 4 and the flexural strength results in Figs. 5 and 6. The reported compressive and flexural strengths for each concrete mix are the average results of testing three specimens.

5.1 Effects of Granite Waste on Compressive Strength before Heating

Figs. 3 and 5 show that substituting 50% of the silica sand with GW in concrete mixes with 1400 kg/m³ (M1 to M4) and 1200 kg/m³ (M5 to M8) binder content, the mechanical properties improved and compromised, respectively, before heating. In general, because of its finer grading than silica aggregates, GW serves as filler, if sufficient cement paste is available to cover the entire surface of aggregates, and

increases the compaction of the concrete and improves the transition zone and, consequently, the mechanical properties, including the compressive and flexural strengths. In concrete mixes with a 1400 kg/m³ binder content (M1 to M4), incorporating GW into the concrete to replace silica sand improves compressive and flexural strengths due to the sufficient amount of paste in the concrete. However, in concrete mixes with a 1200 kg/m³ binder content (M5 to M8), GW replacement of silica sand results in a loss of mechanical properties due to lack of enough binder to cover the entire surface of the aggregates. Fig. 7a, b shows the transition zone in specimens with 1400 and 1200 kg/m³ binder contents, respectively. Fig. 7a shows the aggregates perfectly is covered by cement paste, but in Fig. 7b, porosities appear in the covered transition zone due to the lack of enough paste. Fig. 8 shows the results of the XRD test

Fig. 12 Variation of flexural strength of concrete mixes against SF/B before and after heating
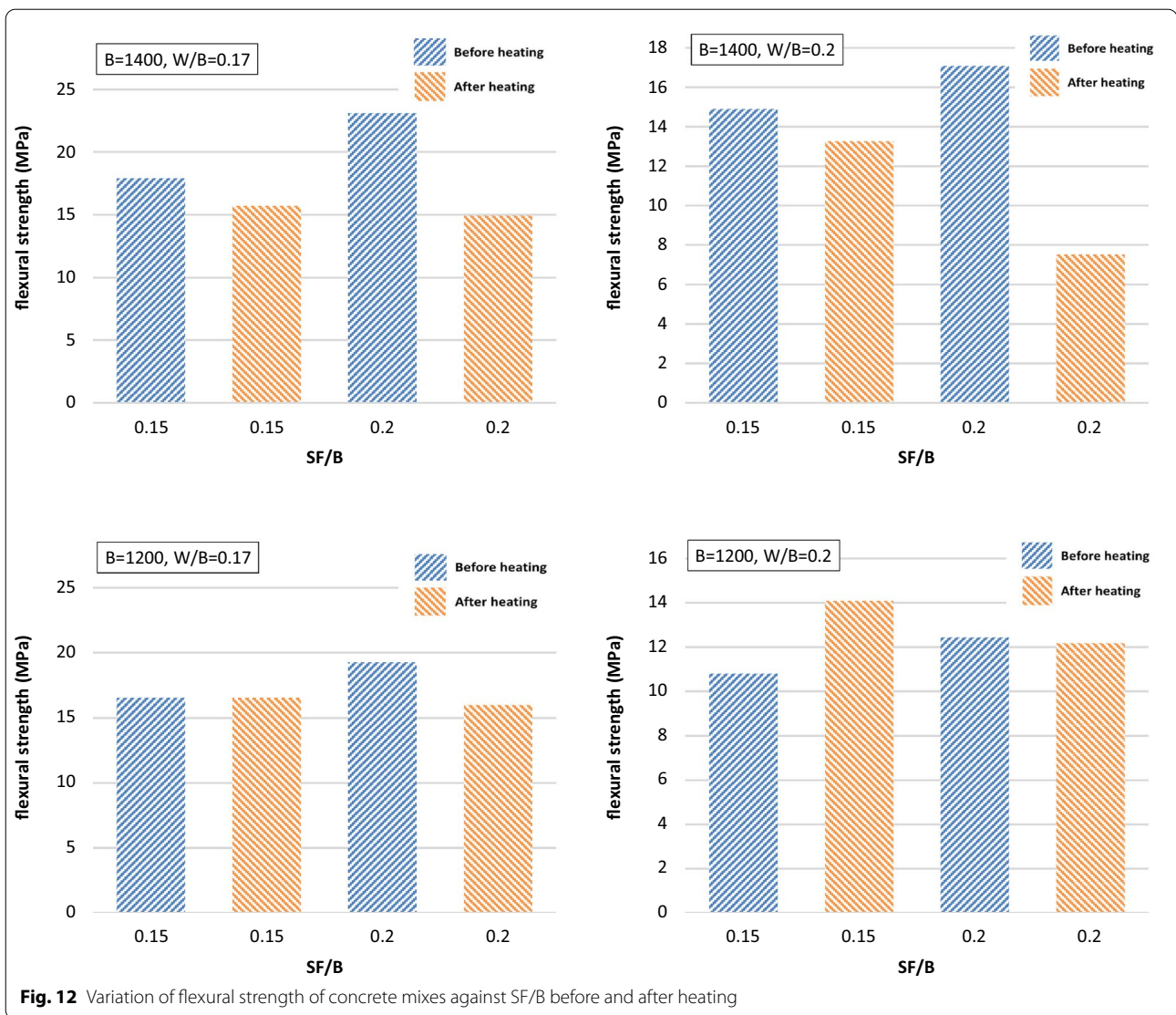
performed on M7 and MG7 concrete mixes before heating. As can be seen, in the MG7 concrete mix, due to the use of GW in addition to the formation of Gehlenite in concrete specimens without GW, the use of granite can affect the increase in the compressive strength on the condition of sufficient cement paste to cover the aggregate.

5.2 Effects of Key Parameters on mechanical properties of Refractory concrete mixes without GW

5.2.1 Effects of binder content

Figs. 9 and 10 plot the compressive and flexural strengths of concrete mixes against binder content before and after heating. As evident from the figures, in all concrete mixes, increasing the binder content helps improve the compressive and flexural strengths before heating. As the binder (cement + silica fume) content is increased, amount of water is also increased, and therefore, more paste is available to cover the aggregates in the concrete matrix and enhance the compressive and flexural strength.

Figs. 9 and 10 also indicate that adding more binder decreases both compressive and flexural strengths after heating in all the concrete mixes. As discussed earlier, adding more binder increases the compaction of the concrete. Therefore, the steam developing in the specimens at 1200 °C cannot escape the concrete easily and increases pore pressure, resulting in surface cracks and

Fig. 13 Variations of compressive strength of concrete mixes against W/B before and after heating
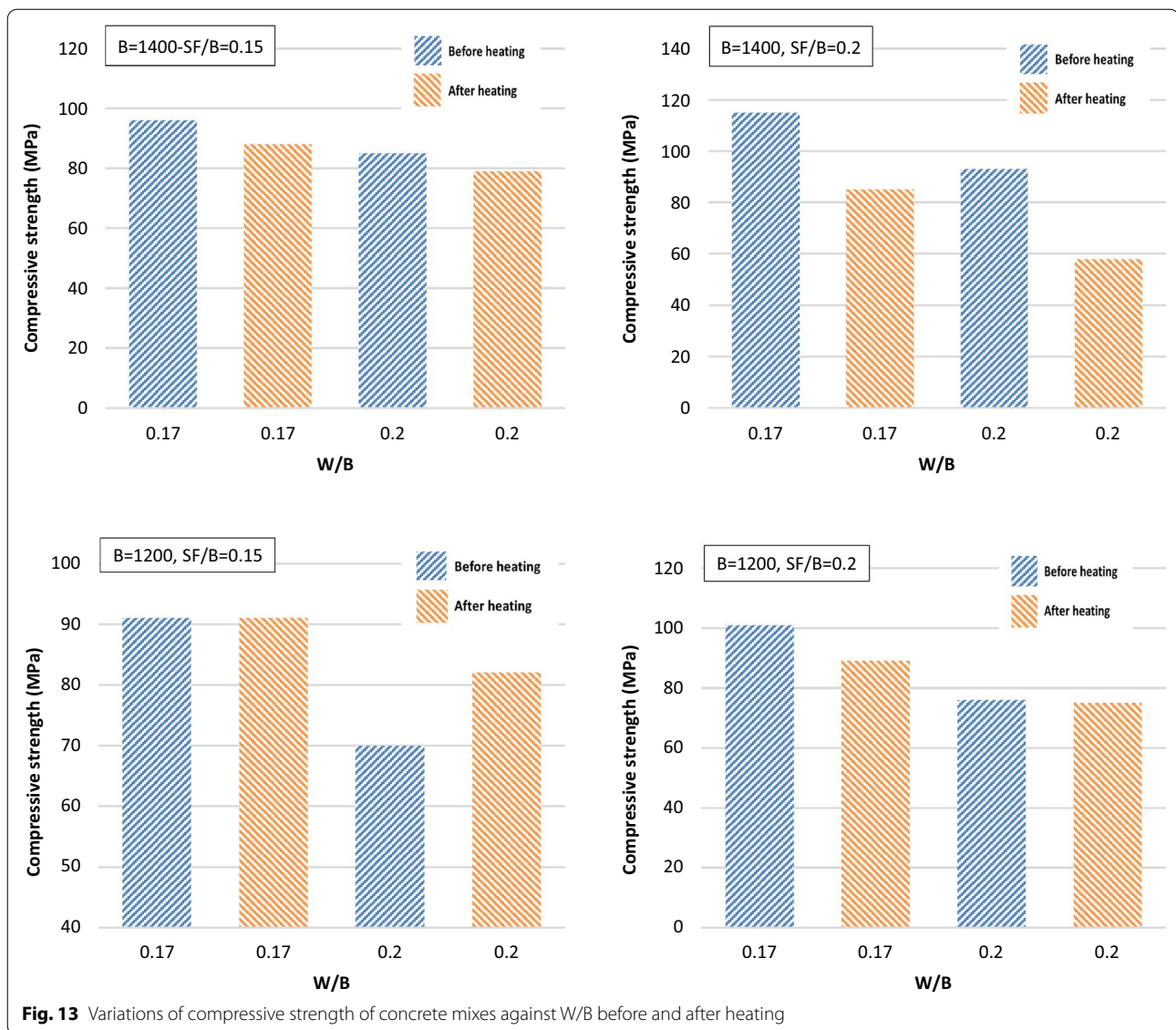
micro-cracks inside the concrete, undermining the compressive strength.

5.2.2 Effects of silica-fume-to-binder ratio on mechanical properties

Figs. 11 and 12 plot variations of compressive and flexural strengths of concrete mixes against silica-fume-to-binder (SF/B) ratio for the different concrete mixes before and after heating. Evidently, increasing the silica fume content increases mechanical properties before

heating and decreases them after heating in all the concrete mixes. As shown in various references and can be seen in Fig. 8, due to the hydration of alumina cement containing silica fume, Gehlenite is formed, which has properties similar to C–S–H in the ordinary concrete. Therefore, with increasing the amount of silica fume, the amount of hydrated Gehlenite and calcium silicate increases and the amount of C3AH6 (which is the final product of hydration of CAC at ambient temperature) decreases, and consequently, the mechanical properties
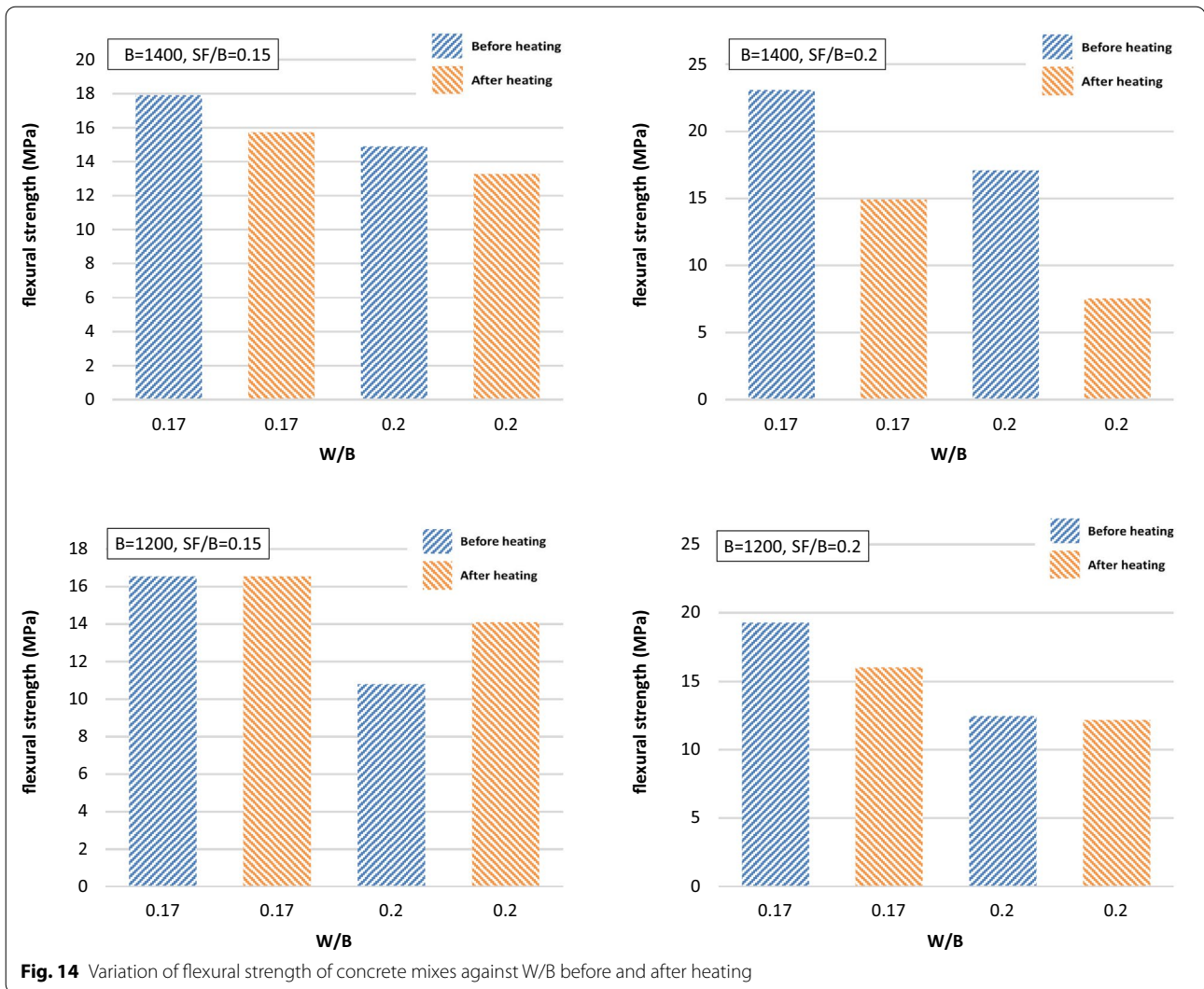
Fig. 14 Variation of flexural strength of concrete mixes against W/B before and after heating
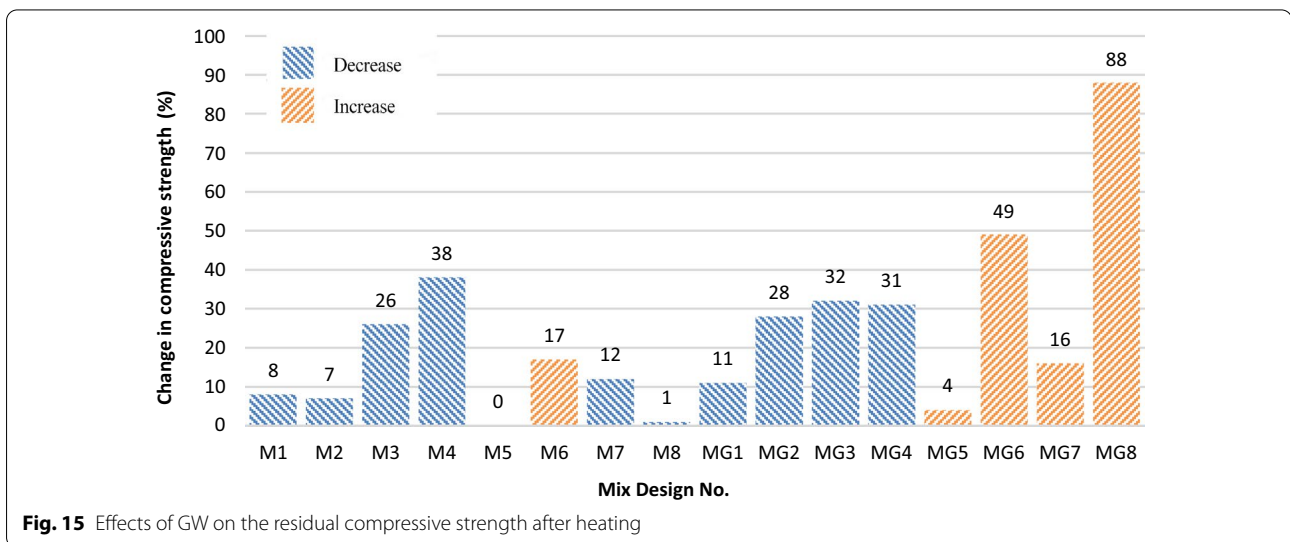
Fig. 15 Effects of GW on the residual compressive strength after heating
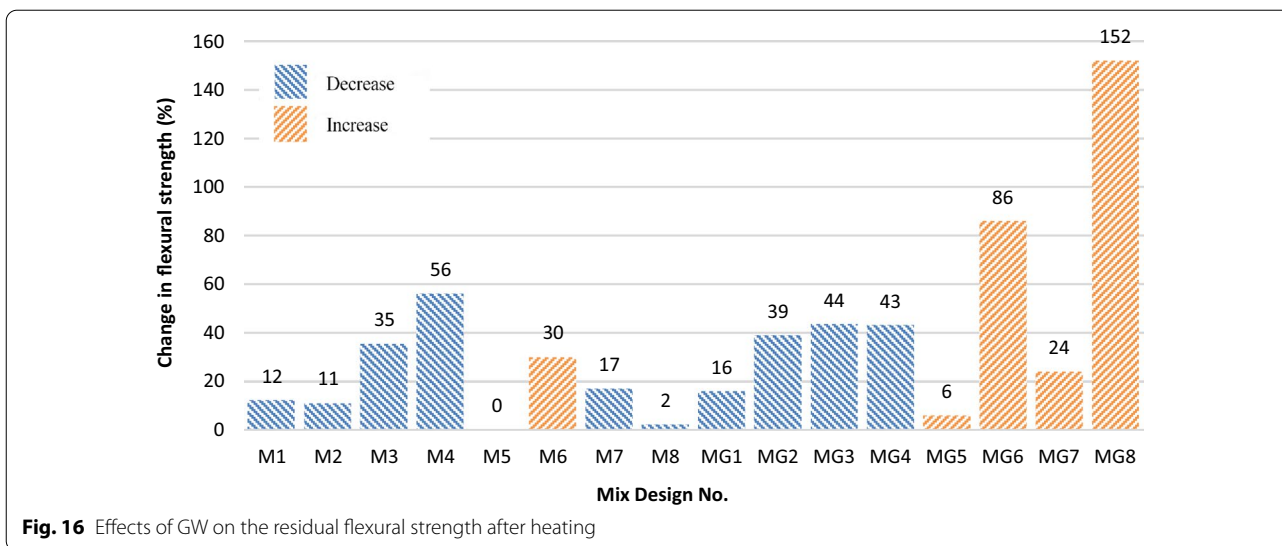
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Fig. 16 Effects of GW on the residual flexural strength after heating

improve.(Bareiro et al., 2018; Hewlett; Hidalgo et al., 2009).

When concrete specimens containing silica fume were exposed to heat, due to the dehydration of the compounds formed inside the concrete and the filling properties of the silica fume, the water vapor formed inside the concrete is not able to leave the concrete pores, which causes pressure. It causes pores and stress inside the concrete, which causes stress in the concrete and the growth of micro-cracks inside the concrete, and ultimately reduces the mechanical properties (compressive and flexural strength).

5.2.3 Effects of water-to-binder ratio on mechanical properties

Figs. 13 and 14 show the variations of compressive and flexural strengths, respectively, of the concrete mixes before and after heating in terms of the water-to-binder (W/B) ratio. Evidently, compressive and flexural strengths reduced at higher water-to-binder ratios in all the mixes at both before and after heating. The loss of the strengths before heating can be attributed to the pores remaining from the excess water in the concrete. Overall, when the free-water content of the concrete increases, the drying of the liquid leaves behind empty voids. In other words, with more free water in the concrete, more voids develop, increasing the porosity and, ultimately, compromising the mechanical properties.

The loss of compressive and flexural strengths after heating at higher W/B ratios can be attributed to the increasing pore pressure by steam formation. As discussed earlier, the CAH_{10}, C_2AH_8, C_3AH_6, and AH_3 crystals forming by CAC hydration contain 53, 40, 28, and 35% water, respectively, and release some water into the

concrete after dehydration. Increasing the W/B ratio promotes crystal formation and, consequently, increases the amount of water absorbed by the crystals. Following heating and dehydration, some water is released into the concrete, which is partially used up in reacting with other crystals to form new crystals, while the remainder stays as excess water. The excess moisture evaporates at high temperatures, building up pore pressure. Increasing the W/B ratio results in higher water content and, consequently, higher pore pressure, reducing the compressive and flexural strength.

Regarding the effects of these parameters on high-strength refractory concrete with GW, it is safe to say that effect of the discussed parameters on con concrete with GW and without GW is the same.

5.3 Effects of GW on compressive and flexural strength loss after heating

Figs. 15 and 16 show changes in compressive and flexural strengths of concrete mixes after heating. The figures indicate that in concrete mixes with 1200 kg/m^3 binder content and containing GW (MG5 to MG8), unlike mixes without GW (M5 to M8), not only the compressive and flexural strengths do not decline after heating but also increases. This can be attributed to the sintering and formation of a single mass by heat and pressure without reaching the melting point. As discussed in the previous section and Fig. 17, the hydration of concrete mixes containing alumina cement and silica fume forms Gehlenite crystals and hydrated aluminum silicate calcium. Since the melting point of Gehlenite is 1400 °C, with increasing temperature, hydrated calcium silicate is dehydrated and converted to calcium oxide ($CaAl_2O_4$) with a melting point of 1600 °C. In addition, by examining the XRD
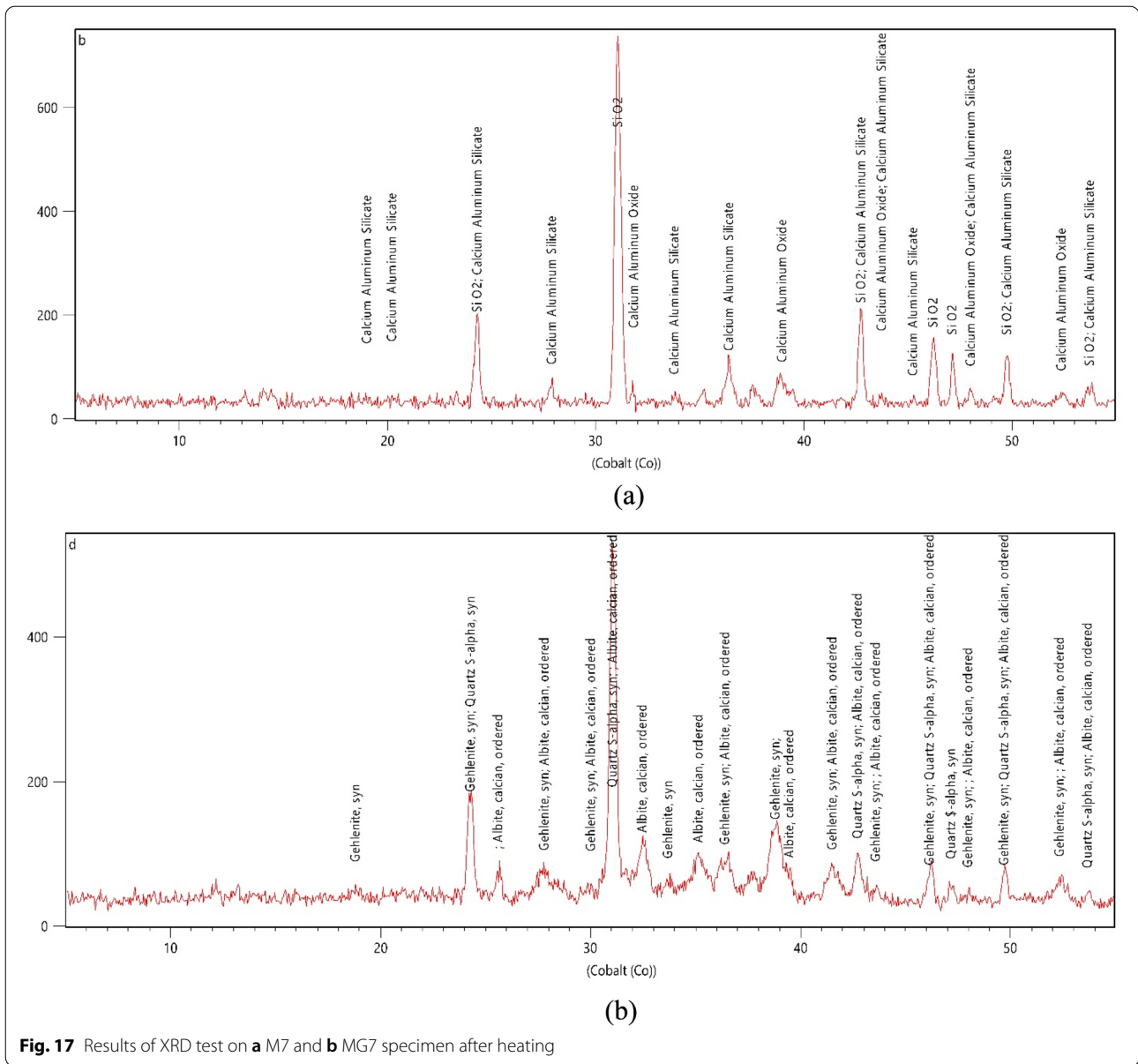
Fig. 17 Results of XRD test on **a** M7 and **b** MG7 specimen after heating

results, it can be seen that Albite materials are still present in the concrete after heating despite the melting point of 1200 °C. Since all newly formed crystals melt in the 1200–1400 °C range, partial replacement of silica aggregates (with a melting point of 1700 °C) with GW that melts at 1260 °C causes that some of the aggregates melt in the same temperature range as cement crystals, leading to the sintering of refractory concrete. In this case, concrete crystals and the GW turn into paste at 1200 °C and are compacted by the water pressure caused by the dehydration of concrete crystals, forming much

stronger bonds than the initial ones, improving the compressive and flexural strengths of the concrete. Fig.18a, b shows SEM images of specimens with and without GW after heating. To prepare SEM images, 1 g of each concrete sample was initially dried in the oven and exposed to a gold coating. The accelerating voltage of the scanning electron microscope (SEM) was set to 20.0 kV and the takeoff angle to 35.5°. The sintered particles appear as white polygons in Fig. 18a, whereas crystals shown in Fig. 18b have formed irregularly and scattered.

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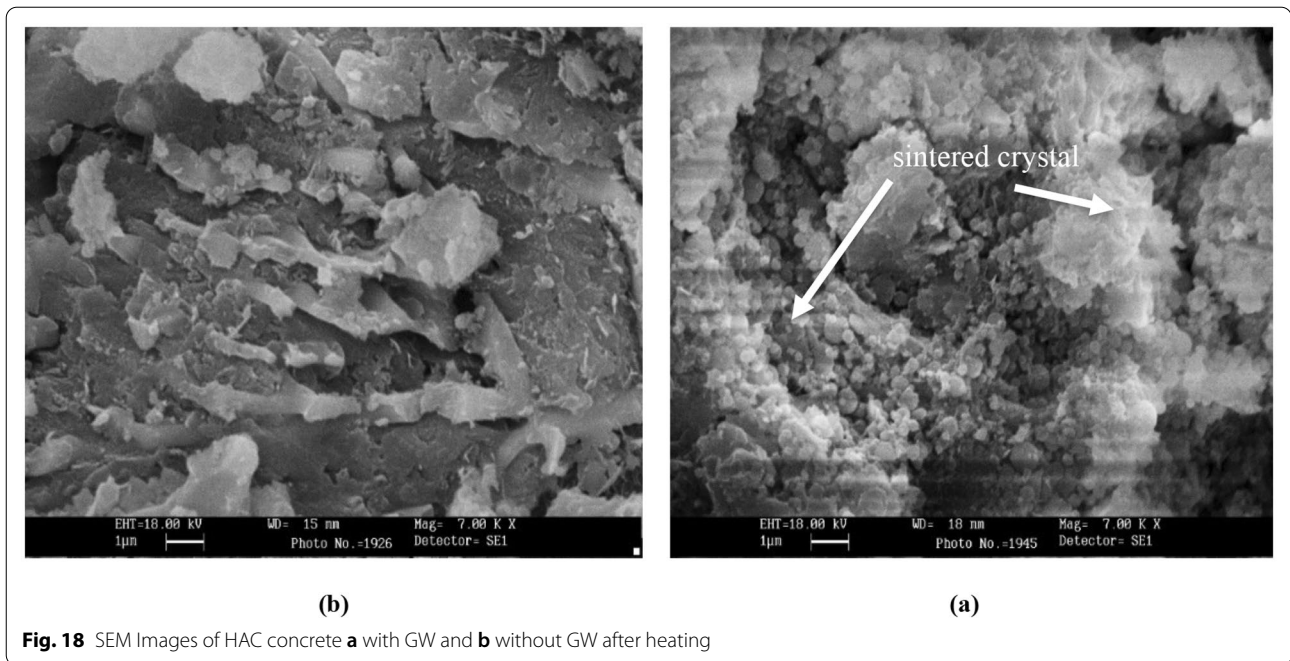
Fig. 18 SEM Images of HAC concrete **a** with GW and **b** without GW after heating
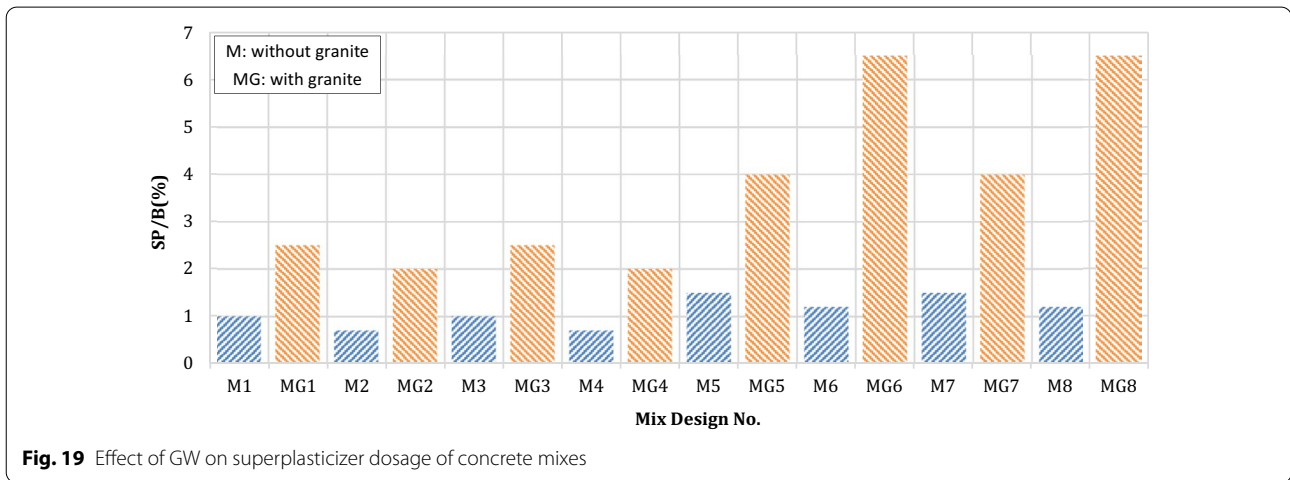
Fig. 19 Effect of GW on superplasticizer dosage of concrete mixes

In mixes MG5 to MG8, with 50% GW, heating the concrete to 1200 °C increased the compressive and flexural strengths due to sintering. In MG1 through MG4, due to the considerable binder content (B = 1400 kg/m^3) and the formation of hydrated calcium aluminum oxide crystals (CaAl$_2$O$_4$) with a melting point of 1600° C instead of Gehlenite with a melting point of 1400° C sintering phenomenon does not occur.

The negligible strength loss and even increase of strength in some cases of the specimens without GW, namely, M5 through M8, after exposure to high temperature can be attributed to the Gehlenite formation in concrete. As can be seen in Fig. 17, there is a large amount of calcium aluminum silicate or Gehlenite in concrete without granite, which despite the use of silica aggregate, there is still the possibility of sintering due to the high volume of this material, but from there The volume of materials and aggregates with the same melting point in this concrete is low, the volume of sintered crystals is much less than samples containing granite (Zawrah et al., 2011).

5.4 Effects of Using GW on the Required Amount of Plasticizer

As discussed earlier, plasticizer content was adjusted to ensure a 200 ± 10 mm spread diameter in the flow

table test. Fig. 19 illustrates the effects of using GW on superplasticizer dosage. It is observed that adding GW to the high-strength refractory concrete increased the required amount of superplasticizer. In this case, the GW was finer than the silica sand and, therefore, had a larger surface area. As the amount of cement paste was fixed, the concrete with GW was less fluid than the one without GW. Accordingly, the same level of fluidity will be achieved using more superplasticizer.

6 Summary and Conclusion

Aiming to assess the feasibility of using GW in eco-friendly high-strength refractory concrete, as a step toward sustainable development, this study compared sixteen concrete mixes, including two W/B ($=0.17$ and 0.2), two SF/B ($=0.15$ and 0.2), two binder contents (B$=1200$ and 1400 kg/m^3), and two ratios of replacement of silica sand by granite waste (GW/Agg$=0$ and 50%). Superplasticizer dosage was adjusted to achieve a 200 ± 10 mm spread diameter for all the concrete mixes. Compressive and flexural strength tests were carried out on each concrete mixture specimens. The results can be summarized as follows:

- Increasing the binder content in mixes with and without GW improved their compressive and flexural strengths before heating. Furthermore, the higher compaction of the concrete containing more binder increased the vapor pressure due to the dehydration of crystals, reducing the strengths after heating by developing more micro-cracks.
- Adding more silica fume to the HAC concrete mixes with and without GW enhanced the compressive strength of the specimens before heating by forming stronger crystals. Given the lower melting point of these crystals compared to those of the concrete without silica fume, increasing SF/B led to a reduction in compressive strength due to heating.
- The higher W/B lowered the compressive and flexural strengths before heating by increasing porosity in mixes with and without GW. Moreover, after heating by increasing W/B of mixes, mechanical properties decrease due to the increased vapor pressure.
- Substituting silica aggregates with GW in concrete mixes with B$=1400$ kg/m^3 increased the compressive and flexural strengths before heating by 3–15% and 4–25%, respectively, due to formation of more dense crystals, whereas in concrete mixes with B$=1200$ kg/m^3, this replacement reduced the strengths by 0% and 12%, respectively, due to the lack of sufficient aggregate coverage.
- In HAC concrete with B$=1200$ kg/m^3, replacing silica aggregates with GW enhanced the strengths

of the specimen after being exposed to 1200 ^{0}C temperature by 20–78% and 15–60%, respectively, due to sintering. In contrast, using GW in the concrete specimen with B$=1400$ kg/m^3 exacerbated the loss in the compressive strength due to heating

- As GW is finer than silica sand, it has a larger surface area. Therefore, using GW in the concrete required more superplasticizer to maintain the same level of fluidity.
- Powder high-strength refractory concrete can be used to make high-strength refractory components. Each cubic meter of the studied concrete mixes use 400–1000 kg of aggregates. Accordingly, at a 50% replacement ratio of the aggregates by GW in the high-strength refractory concrete, 200–500 kg GW is used up, which supports sustainable development and helps protect the environment.

Authors' contributions
KS and MSS: formal analysis, investigation, resources, data curation, and writing—original draft. MR: conceptualization, methodology, validation, and writing—review. All authors have read and approved the final manuscript.

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