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Blended cement containing high volume ground dune sand and ground granulated blast furnace slag for autoclave concrete industry

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Abstract. This paper presents the results of using ground dune sand (GDS) and ground granulated blast furnace slag (slag) as high volume cement replacement materials. In this study, plain and four blended mixtures were fabricated and cured under normal and autoclave conditions. For the blended mixtures, 40% GDS by weight of the total binder materials and different percentages of slag (15%, 30% and 45%) were incorporated as partial cement replacement materials. The effect of curing conditions (normal and autoclave) on the compressive strength of prepared mixtures was studied. The results showed that, for the autoclave cured mixture, up to 85% of cement can be replaced by GDS and slag without significant drop in the compressive strength. Microstructure analyses using scanning electron microscope (SEM) and X-ray diffraction analysis (XRD) were carried out to examine the microscale changes of the hydrated mixtures. The SEM revealed the formation of thin plate-like calcium silicate hydrate and compacted microstructure of autoclave cured mixture. XRD showed the elimination of calcium hydroxide and existence of residual crystalline silica of all blended mixtures.

Introduction

Concrete is a composite material consists of aggregates, water and cement. When cement gets contact with water, several chemical reactions (hydration) are occurred resulting in a cement paste that binds the aggregate together. To ensure the continuity of cement hydration, the cast mixture should be cured under appropriate conditions. The typical curing conditions used in concrete technology include: normal curing, hydrothermal curing, membrane curing, etc. The so called normal (standard) curing is conducted under moist and ambient temperature. During this condition, the hydration process and strength development rate of concrete are slow [1]. Accordingly, concrete cured under normal conditions takes several days, perhaps several months to reach the ultimate strength [2]. In the precast concrete factories, higher early strength which enables handling, transportation and reducing storage costs of the cast concrete elements is an important parameter [3, 4]. Therefore, accelerating curing conditions such as hydrothermal curing is adopted for this technology.

High pressure steam curing (autoclave curing) is applied in a closed chamber to achieve high early strength [5-7]. The whole steam curing cycle is suggested to be completed within few hours or days [8]. Other advantage of autoclave curing is that many kind of siliceous materials can be used as supplementary cementing materials, even though some siliceous materials may not be feasible to react under normal curing conditions as in the case of crystalline silica. Ground dune sand (GDS) which consists of crystalline silica has been used as a source of siliceous material in autoclave concrete [9]. The incorporation of GDS enhanced the compressive strength, where the maximum compressive strength achieved at 30% level of cement replacement. The aim of this study was to investigate the effect of incorporating GDS and slag as high volume cement replacement materials for autoclave

concrete industry. The successful use of this combination can have a significant impact on the sustainability and economy of concrete construction.

Experimental work

Raw material. In this study, the utilized dune sand used was obtained from Riyadh, Saudi Arabia. The natural dune sand was mechanically ground until 95% were passing 45 μm in size. The chemical composition of the GDS is presented in Table 1. Also, the XRD of GDS is shown in Fig. 1(a). It is worth mentioning that Portland cement (PC) complies with ASTM C150 and slag of grade 100 (ASTM C 989) were used in this study. The chemical composition of PC and slag is shown in Table 1, and the XRD of slag is shown in Fig. 1(b). Water tab and mining sand with maximum particle size of 2.36 mm were used to fabricate mortar mixtures. The specific gravity and fineness modulus of the mining sand was 2.5 and 2.49, respectively.

Table 1. Chemical composition of PC, GDS and slag.

Binder	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
PC	22.62	6.11	3.69	57.96	2.16	0.98	0.17	2.99	3.02
GDS	93.4	0.19	0.32	0.45	-	0.04	-	-	1.15
slag	33.33	13.74	0.44	43.1	5.76	0.41	0.2	1.89	1.34

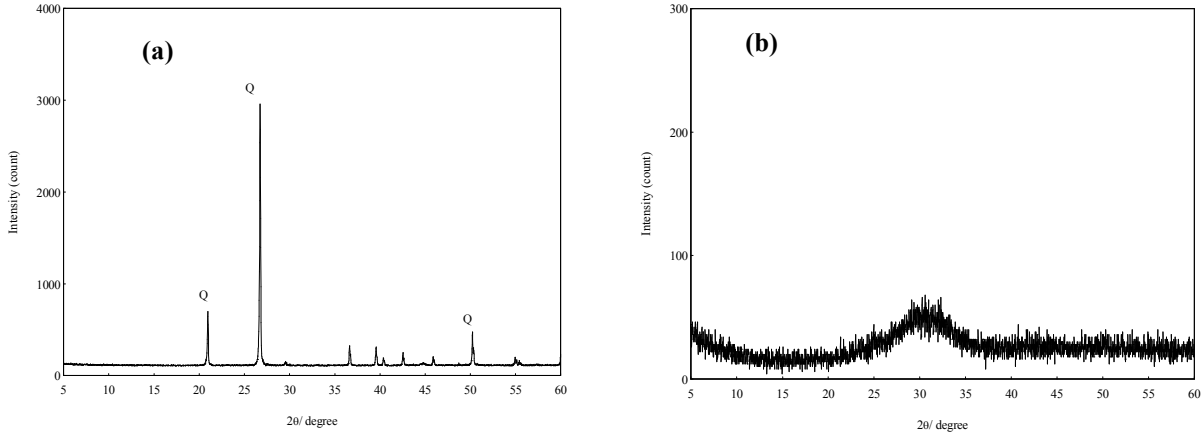


Fig. 1 XRD pattern (a) GDS and (b) slag.

Sample preparation. The mixtures used in this study consists of control and four ternary blended mixtures (GDS+slag+PC). For the blended mixtures, 40% by weight of GDS was held constant and different concentrations of slag were used as further PC replacement. The incorporation levels of slag were 0%, 15%, 30% and 45% (by weight). Control and ternary blended mixtures were formulated with fine aggregate: binder: ratio of 3, and water: binder of 0.3. The mixtures were denoted as M1, M2, M3, M4, and M5 and their binder composition details are summarized in Table 2.

Table 2. Binder proportions for the ternary blended cement mixtures.

Mixture ID	Binder content %		
	PC	GDS	Slag
M1	100	-	-
M2	60	40	-
M3	45	40	15
M4	30	40	30
M5	15	40	45

Nine 50 x 50 x 50 mm cubic samples were prepared for each mixture according to ASTM C 305. The samples were cast and compacted on a vibrating table for approximately 5 to 12 seconds. The cast samples were covered with plastic sheets and kept in laboratory conditions (23±3 ºC and 50 ±5 relative humidity) for 24 h. The samples were then demoulded and cured under either normal conditions (immersion in water at 23 ± 3 °C) or autoclave conditions. The samples cured under autoclave condition were first held in standard conditions for 16 h and then placed in the autoclave chamber. The chamber temperature was increased from room temperature to 182±3 °C within 1 h. Consequently, the pressure was increased from atmospheric pressure to 1.0 MPa. The temperature and pressure were maintained constant at 182 ± 3 °C and 1.0 MPa for 5 h, then the autoclave heater was turned off and the chamber allowed cooling naturally. The room temperature was reached in about 1.5 h.

Compressive strength tests were carried out according to the ASTM C 109. The average strength value of three samples is reported for each testing. Cement pastes made of similar blended binder combination of mortar mixtures were prepared for microstructure study. SEM and EDX analyses were carried out using Jeol JSM 6610LV. Samples for SEM analysis were prepared by taking fractured surface specimen of the cured pastes. The chemical composition analysis of selected spots (field of view) was carried out using energy-dispersive X-ray spectroscopy (EDX). XRD analysis was conducted using a Shimadzu XRD-6000 diffractometer with a scanning rate of 2° /min from 10° to 60° (2θ) to give mineralogical information of each sample.

Results and discussion

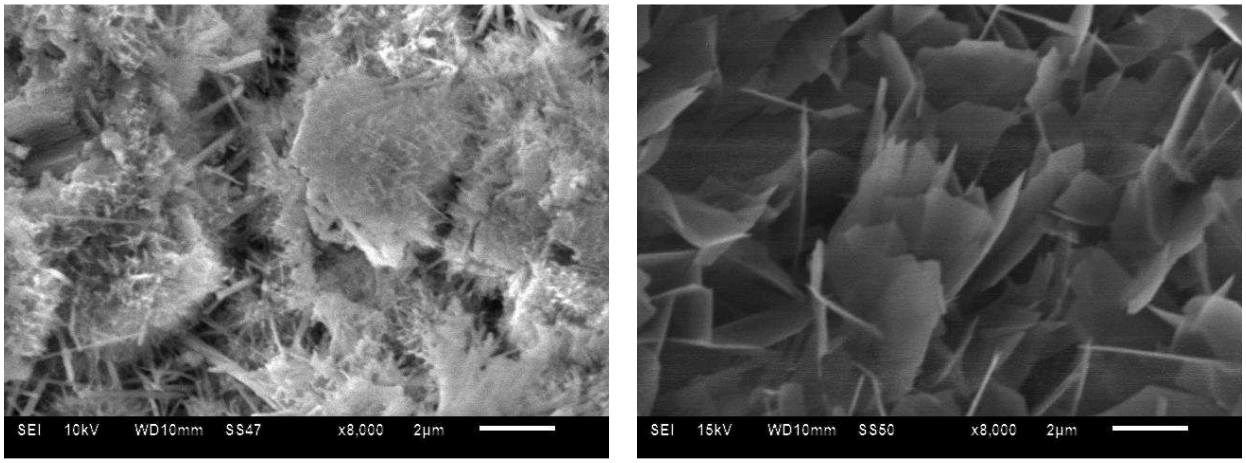
Compressive strength. Table 3 shows the compressive strength results of ternary combinations of GDS, slag and PC mixtures (M1-M5) cured under normal and autoclave conditions. For the normal curing (NC), all blended mixtures have lower compressive strength compared to control (M1) mixture at both 7 and 28 days. The level of reduction varied between 21% and 33% at 7 days and between 34% and 43% at 28 days. The reduction can be attributed to lesser cement content in the mixtures, increased water to cement ratio and GDS acted as a filler materials. For autoclave curing (AC), M2 mixture (40% GDS) has yielded compressive strength higher than that of the control mixture cured at 28 days (M1-NC) by about 16%. Inclusion of slag as further PC replacement at 15%, 30% and 45% maintained the compressive strength between M1-NC and the M2-AC (66 MPa – 78 MPa). The enhancement in the compressive strength can be attributed to the fact that under autoclave curing, crystalline SiO_2 in GDS reacted with calcium hydroxide (CH) generated from the hydration of cement. Accordingly, additional cementitious matrixes are produced. The results revealed that GDS and slag can be used to replace up to 85% of PC without significant drop in the compressive strength. This is because under autoclave conditions additional cementitious matrixes are produced from the hydration of slag and reaction between SiO_2 in GDS and CH.

Table 3. Compressive strengths of control and blended mixtures cured under normal and autoclave conditions

Mixture ID	Compressive strength, MPa		
	7 days (NC)	28 days(NC)	AC
M1	48	67	63
M2	32	38	78
M3	34	43	73
M4	38	44	71
M5	36	44	66

Morphological study. Fig. 2 (a and b) shows SEM images of M1-NC and M5-AC mixtures. Plates of CH, needle-like forms of ettringite and black pores were observed from M1-NC morphology (Fig. 2(a)). These features are consistent with those reported in the literature [10]. Also, Fig 2(a) reveals

that the hydrated products are associated with open network structures. Regarding the autoclave cured mixture (M5-AC), plate-like structures of tobermorite were observed (Fig. 2(b)). In addition, the M5-AC mixture revealed dense, compacted and close network structures. This structure explained the enhancement effect in the compressive strength of blended mixtures cured under autoclave conditions compared to that cured under normal conditions.



(a) M1-NC (b) M5-AC

Fig. 2 SEM image of (a) M1- NC and (b) M5-AC

Fig. 3 presents the image and EDX analysis of M5 cured under autoclave conditions. The EDX analysis shows the presence of Si, and Ca in high concentration indicating the formation of rich silica -calcium silicate hydrate (CSH) such as tobermorite. Previous study demonstrated that tobermorite formed under autoclave curing is associated with high strength and low porosity [11].

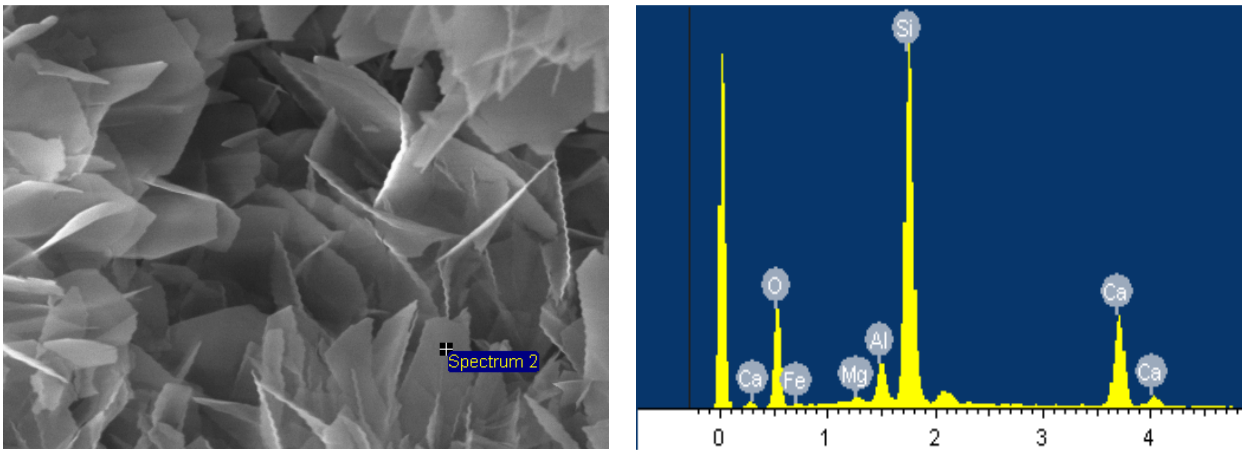


Fig. 3 EDX analysis of M5-AC mixture

XRD analysis. Fig. 4 shows the XRD patterns of the control and ternary blended mixtures (M1-M5) cured under autoclave conditions. For the M1 mixture, crystalline peak at 29.5°-31° (2θ) corresponding to the α-dicalcium silicate hydrate (α-C2SH) was observed. For (M2-M5), residual quartz peaks at 2θ° 21° and 26.5° were detected in all blended mixtures, while, no calcium hydroxide (CH) peaks were observed. The residual quartz peaks are attributed to the presence of excess crystalline silica in the blended mixtures. Moreover, the incorporating of slag as ternary blended element did not consume the remaining crystalline silica. These results indicated that the CaO provided from slag reacted rapidly with SiO_2 and Al_2O_3 generated from the slag itself resulting in no free CaO to combine the un-reacted crystalline silica of GDS. Therefore, in order to utilize the excess crystalline silica, material rich in CaO should be added.

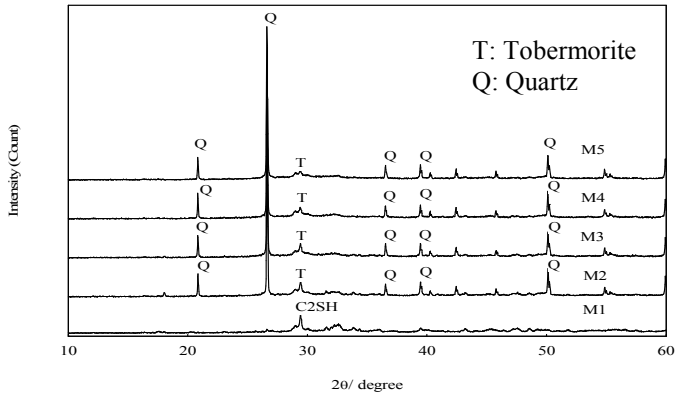


Fig. 4 XRD analysis of M1 – M5 mixtures curd under autoclave condition

Conclusion

This paper studied the effect of incorporating the GDS and slag as PC replacement and their influence on the compressive strength and microstructure properties. It can be concluded that, under autoclave conditions, incorporating of GDS and slag as high volume PC replacement materials improved the compressive strength and microstructure properties of the concrete. GDS and slag can replaced up to 85% of PC without significant drop in the compressive strength. SEM analysis showed the formation of thin crystalline CSH phases with compacted network structure of autoclaved cured mixtures. In addition, residual crystalline silica were observed from the all ternary blended mixture, whereas, CH peaks had disappeared.

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