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Binary and ternary effects of ground dune sand and blast furnace slag on the compressive strength of mortar

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ABSTRACT

The aim of this study is to promote the use of available natural dune sand from desert areas as a partial cement replacement. Binary and ternary combinations of ground dune sand (GDS), Portland cement (PC) and ground granulated blast furnace slag (GGBS) were investigated for their effects on the compressive strength of mortar cured under standard or autoclave curing conditions. The results showed that the compressive strength decreased significantly with increasing GDS and GGBS contents under standard curing. However, with autoclave curing, all of the binary and ternary mixtures yielded mortar with a compressive strength higher than that of the control sample. The autoclave-cured ternary combination of 30% GDS, 50% PC and 20% GGBS showed the highest compressive strength. It is possible to use a PC content as low as 10% since the mixture of 30% GDS, 10% PC and 60% GGBS displayed strength comparable to the control sample.

1. Introduction

The production of concrete containing blended cement has experienced rapid growth in the construction industry. One motivation for this increase is the desire to reduce the consumption of Portland cement (PC) due to its energy-intensive production process, involving significant resource consumption and the emission of a considerable amount of carbon dioxide (CO_2) into the atmosphere. The production of one ton of PC releases approximately one ton of CO_2 [1]. Therefore, to save energy, resources and the environment, considerable attempts are being made to find substitute materials that can be used as a partial replacement of PC. Supplementary cementitious materials (SCMs) such as fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), metakaolin (MK) and rice husk ash (RHA) are some of the most common PC replacement materials currently used in the concrete industry. The incorporation of these materials provides technical, economic and environmental benefits [2]. The technical benefits include the enhancement of fresh concrete properties and finished concrete with increased ultimate compressive strength and improved impermeability and durability [3]. Concrete made with SCMs prevents the consumption of a large volume of PC; thus, the total cost of cubic meter of concrete can be reduced, and the total CO_2 emission minimized [4].

The SCMs are alumino-silicate materials which in the presence of moisture react with calcium hydroxide (CH) at ambient temperature to form the cementitious calcium silicate hydrate (CSH) [5,6]. The absence of CH has a positive effect on the durability and the transition zone between cement paste and aggregate [7–9]. Apart from their chemical effects SCMs help to fill the capillary pores between cement grains and thus improve the density of the cement paste [10]. Moreover, the fine particle size of many SCMs provides more nucleation sites for further hydration, thus accelerating the hydration of PC [11,12].

Unlike other SCMs, GGBS consists of chemical oxides similar to those in PC but in different proportions [3]. Many studies have been conducted on the use of GGBS as an SCM. It has been documented that the GGBS-supplemented concrete shows a lower early strength gain compared with plain concrete [4]. Therefore, GGBS is not used in applications where high early strength is required. However, when GGBS is added in combination with PC, the hydration of GGBS is accelerated due to the presence of CH and the sulfate compound gypsum in the PC. It has also been reported that the reactivity of GGBS is improved at elevated temperatures [13,14].

Thermal curing is usually applied in the precast concrete industry to accelerate early strength development. The compressive strength obtained with 28 days of normal curing can easily be achieved in 24 h under high-pressure steam curing (autoclave curing). The use of autoclave curing not only accelerates the hydration of Portland cement but also activates the less reactive silica [15].

Aldea et al. [16] studied the effects of different curing conditions on the properties of slag-supplemented concrete. Their

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results showed that up to 50% of the PC could be replaced with slag without affecting the strength of concrete cured under autoclave conditions. Shi and Hu [17] studied the reactivity of ladle-slag concrete cured in an autoclave. They concluded that the combination of ladle slag with fine quartz or silica flour resulted in high compressive strength. In addition, they found that incorporating small amounts of PC or hydrated lime to this combination yielded further improvements in the compressive strength.

A number of studies have shown that crystalline silica performs better than amorphous silica in autoclave curing [18,19]. Yang et al. [20] investigated the effect of using ground quartz sand (GQS) as an SCM in high-strength concrete. They used autoclave curing to activate the quartz silica in the GQS. Their results revealed that under autoclave curing, the strength increased with increasing GQS content. Jaafar et al. [21] studied the effect of using fine stone dust as a cement replacement material. They concluded that autoclave-cured concrete made of 30% fine stone dust and 70% PC developed strength similar to that of the control concrete mixture cured under standard curing conditions.

Dune sand is an abundant natural material composed mainly of silica in crystalline form [22]. Several studies have been performed with the aim of utilizing this sand as a fine aggregate in the construction industry. However, due to its fine particles of uniform shape, the uses of dune sand have so far been limited to a partial replacement for fine aggregate and a backfilling material [23,24].

Only limited research has been performed on the use of dune sand in powder form as a cement replacement material [25,26]. The objective of this study was to investigate the effect of using ground dune sand (GDS) as a cement replacement material in binary and ternary combinations with PC and GGBS on the fresh properties and compressive strength of mortar. The successful use of GDS to reduce cement consumption can have a potentially significant impact on the sustainability and economy of concrete construction in the Middle East and other countries with unlimited supplies of natural dune sands. The findings of this study may be beneficial for the wider application of dune sand as a cement replacement material in precast concrete, thus reducing PC consumption.

2. Experimental work

The dune sand used in this study was obtained from the desert near Riyadh, Saudi Arabia. The gradation of the original dune sand is presented in Table 1. The dune sand was ground to approximately cement fineness (95% passing a 45 μm opening size) using a ball mill. The chemical composition and physical properties of the GDS are listed in Table 2. The mineralogical analysis and an SEM image of the GDS are shown in Figs. 1 and 2, respectively. Portland cement complying with the ASTM C150 standard and ground granulated blast furnace slag (GGBS) of Grade 100 (ASTM C989) were used in the present study. The chemical composition of the PC and GGBS are presented in Table 2. Standard mining sand with a specific gravity of 2.5 and a fineness modulus of 2.49 was used as a fine aggregate in this study. The gradation of the mining sand is given in Table 1.

The study consisted of two stages. The aim of the first stage was to determine the replacement percentage of PC with GDS in binary blended systems that resulted in a mortar with the maximum compressive strength. The mortar was formulated with binder, sand and water in the ratio of 1:3:0.50, respectively. The binder consisted of PC, GDS and GGBS. Five different percentages of PC (10%, 20%, 30% and 40% on a weight basis) were replaced with GDS, and the mixes were labeled GDS10, GDS20, GDS30 and

Table 1
Original dune sand and standard mining sand gradation.

Sieve size (mm)	Percentage passing (%)	
	Dune sand	Standard mining sand
4.75	100	100
2.36	100	97
1.18	100	79
0.6	95.3	42
0.425	61.2	17
0.3	34	4
0.212	22.8	0
0.15	8.8	0

Table 2
Chemical and physical properties of PC, GDS and GGBS.

Description	Chemical composition (%)		
	PC	GDS	GGBS
SiO_2	22.62	91.4	33.33
Al_2O_3	6.11	0.99	14.74
Fe_2O_3	3.69	0.56	0.61
CaO	57.96	1.68	43.8
MgO	2.16	0.18	3.76
K_2O	0.98	0.21	0.31
Na_2O	0.17	0.05	0.10
SO_3	2.99	0.06	1.89
LOI	3.02	1.15	1.34
Specific surface area, BET (cm^2/g)	3012	2574	5314
Specific gravity	3.15	2.64	2.94

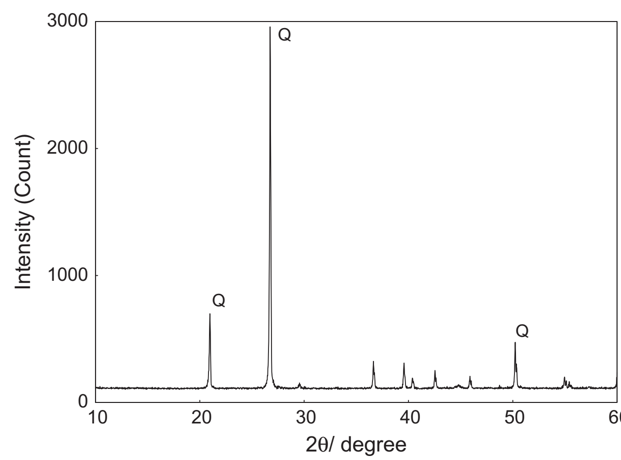

Fig. 1. XRD analysis of GDS.

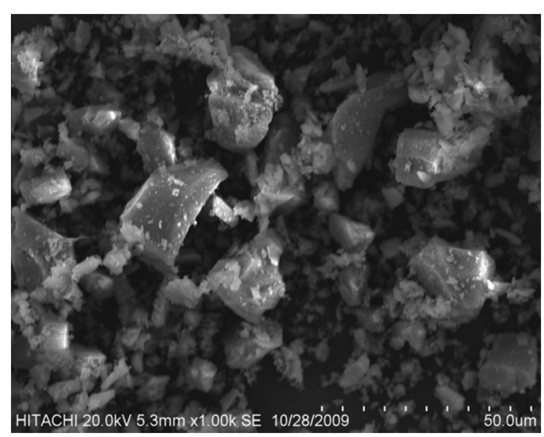

Fig. 2. SEM image of GDS.

GDS40, respectively, as shown in Table 3. A reference or control mix referred to as CTRL with only PC was used for comparison.

After determining the percentage of GDS resulting in the maximum compressive strength, this percentage was used throughout the second stage of the study to determine the possibility of further reducing PC content using GGBS. Thus, the percentage of GDS was held constant at 30%, and six ternary combinations of GDS, PC and GGBS were studied. The combinations are listed in Table 4; they are denoted M1 (30% GDS + 70% PC), M2 (30% GDS + 50% PC + 20% GGBS), M3 (30% GDS + 40% PC + 30% GGBS), M4 (30% GDS + 30% PC + 40% GGBS), M5 (30% GDS + 20% PC + 50% GGBS) and M6 (30% GDS + 10% PC + 60% GGBS). The percentages of these combinations were formulated on a weight basis. In addition, four mixtures containing GGBS as a cement replacement material (at 10%, 20%, 30%, or 40%) were cast and labeled G10, G20, G30 and G40, respectively. These mixtures were cured under autoclave curing conditions to compare their performance with that of the CTRL and the ternary mixtures.

To study the fresh properties of the cement pastes, a Vicat probe and a Vicat needle apparatus were used to determine the standard consistency and setting time of the cement pastes. Additionally, the workability of the mortars was determined using a flow table test according to the ASTM C109 and ASTM C230 protocols.

Twelve 50 mm cubic samples were prepared for each mix (ASTM C305). The samples were cast and compacted on a vibrating table for approximately 30 s. Cast samples were covered with plastic sheets and held at ambient laboratory conditions for 24 h. The samples were then demoulded and cured under one of two curing conditions: standard curing (immersion in water at 23 ± 2 °C) or autoclave curing. Groups of samples were cured under standard conditions for 7, 28 or 90 days. The samples subjected to autoclave curing were first held under standard curing conditions for 16 h and then placed in the autoclave chamber. Autoclaving temperature was increased from room temperature to 182 °C over 1 h. Correspondingly, the pressure was increased from atmospheric pressure to 1.0 MPa. The temperature and pressure were maintained constant at 182 °C and 1.0 MPa for 5 h, and then the autoclave heater was turned off and the chamber allowed to cool naturally. Room temperature was reached in 1.5 h. Compressive strength tests were performed according to the ASTM C109 protocol. The average value of three samples is reported for every testing age group.

3. Results and discussion

3.1. Fresh properties

Table 5 presents the water demand for the standard consistency and the setting times of the binary blended cement pastes. At a replacement level greater than 10%, the water demand for the standard consistency was slightly decreased compared to the CTRL which can be attributed to the similar textures and particle sizes of PC and GDS. The initial and final setting times of these mixtures were increased by approximately 9% and 3%, respectively, in comparison with the CTRL. The increase in the setting time can be explained by the reduced content of C_3A, resulting in less ettringite formation [27].

Table 3
Mix proportions for the binary blended cement mortars (kg).

Mix ID	Mix description	PC	GDS	Fine aggregate
CTRL	PC 100	850	–	2550
GDS10	GDS10PC90	765	85	2550
GDS20	GDS20PC80	680	170	2550
GDS30	GDS30PC70	595	255	2550
GDS40	GDS40PC60	510	340	2550

Table 4
Mix proportions for the ternary blended cement mortars (kg).

Mix ID	Mix description	PC	GDS	GGBS	Fine aggregate
CTRL	PC 100	850	–	–	2550
M1	GDS30PC70	595	255	–	2550
M2	GDS30PC50GS20	425	255	170	2550
M3	GDS30PC40GS30	340	255	255	2550
M4	GDS30PC30GS40	255	255	340	2550
M5	GDS30PC20GS50	170	255	425	2550
M6	GDS30PC10GS60	85	255	510	2550

The normal consistency and the setting times of the ternary blended pastes are presented in Table 6. The incorporation of GGBS as a PC replacement at levels up to 40% did not increase the water demand for the standard consistency, but the initial and the final setting times were increased. This increase in setting time may be due to the delayed hydration process of GGBS and the reduced content of PC [28].

At high GGBS levels, the water required to achieve the standard consistency tended to increase; consequently, its setting time was longer than that of the CRTL paste. This increase in the water demand may be attributable to the larger surface area of GGBS compared with PC (Table 2). The initial and final setting times of all of the binary and ternary pastes were within the range specified by the ASTM C150 standard.

Tables 5 and 6 also present the results for the workability of the binary and ternary blended cement mortars, respectively. This test measures the water required for blended mortars to yield a flow of 110 ± 5%. Substitution of part of the cement with GDS and GGBS slightly increased the water required to yield the standard flow properties. The water-to-binder ratio yielding standard flow for all of the mixes ranged from 0.63 to 0.66.

3.2. Compressive strength

The compressive strength results for the binary blended cement mortars are presented in Fig. 3. With standard curing (SC), the compressive strength values at all PC replacement levels were lower than that of the CTRL mixture. The compressive strength decreased as the percentage of GDS was increased. At 40% GDS replacement, the compressive strength after 28 days of standard curing was approximately half that of the CTRL sample. We concluded that GDS does not react under standard curing conditions. However, with autoclave curing (AC), as illustrated in Fig. 3, the compressive strength of the mortar increased with increasing GDS content at all levels up to 40%. The highest compressive strength was obtained at 30% GDS. Under autoclave curing conditions, the compressive strength of the GDS30 sample was 13% higher than that of the CTRL sample. For the CTRL sample, autoclave curing decreased the compressive strength by approximately 15% compared with the strength at 28 days of standard curing. However, for the GDS30 specimen, autoclave curing resulted in approximately 57% higher strength compared with 28 days of standard curing. The reason for this reduction in the compressive strength of CTRL with autoclaving may be due to a less uniform distribution of hydration products and the formation of α-C_2SH, which is a relatively weak product in comparison with the CSH (gel) generated in standard curing. In contrast, the increase in the compressive strength of the GDS30 sample due to autoclave curing may be attributable to the formation of crystalline CSH products such as tobermorite ($C_5S_6H_5$) or xonotlite (C_6S_6H), which are associated with low porosity and high compressive strength [15,29,30].

The test results for the various ternary combinations of GDS, PC and GGBS are presented in Fig. 4. For all ternary combinations, the

Table 5
Normal consistency and setting times of cement pastes and water requirements for mortar flow in binary blended cements.

Mix ID	Consistency (%)	Setting time (min)		Water-binder ratio (for 110 ± 5% flow of mortar)
		Initial	Final	
CTRL	33	110	180	0.63
GDS10	33	110	180	0.63
GDS20	32	120	185	0.64
GDS30	32	120	185	0.65
GDS40	32	120	185	0.66

Table 6
Normal consistency and setting times of cement pastes and water requirements for mortar flow in ternary blended cements.

Mix ID	Consistency (%)	Setting time (min)		Water-binder ratio (for 110 ± 5% flow of mortar)
		Initial	Final	
CTRL	33	110	180	0.63
M1	32	120	185	0.65
M2	32	123	193	0.65
M3	32.4	123	196	0.65
M4	33	120	200	0.65
M5	33.8	120	210	0.66
M6	34.2	130	230	0.66

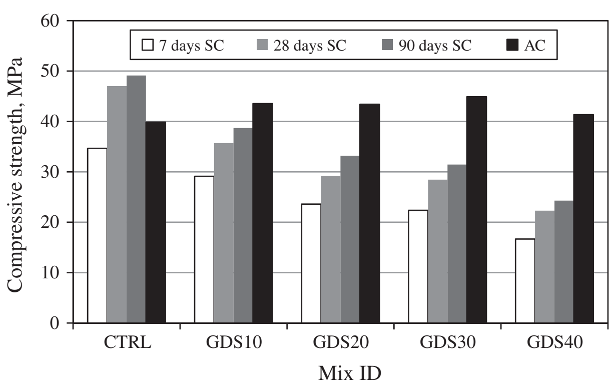

Fig. 3. Compressive strengths of binary blended cement mortars.

compressive strengths at all periods of standard curing are clearly much lower than those of the CTRL samples. However, with autoclave curing, all ternary mixtures had higher compressive strengths than the CTRL mixture. Fig. 5 illustrates the compressive strengths relative to the CTRL mixture of all the autoclave-cured GGBS mixtures, both with and without GDS. It is clear that using GGBS alone caused a slight drop in the compressive strength for all replacement percentages; however, when used in combination with GDS, GGBS improved compressive strength compared with the CTRL mixture.

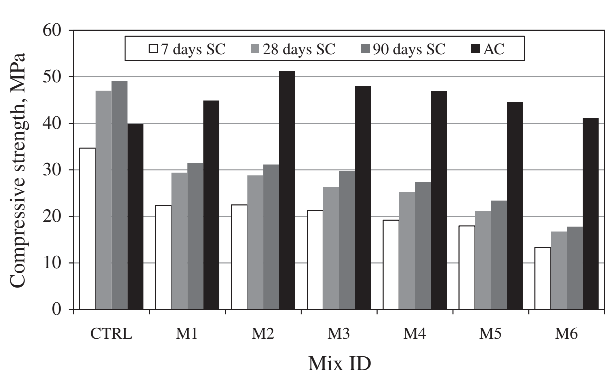

Fig. 4. Compressive strengths of ternary blended cement mortars.

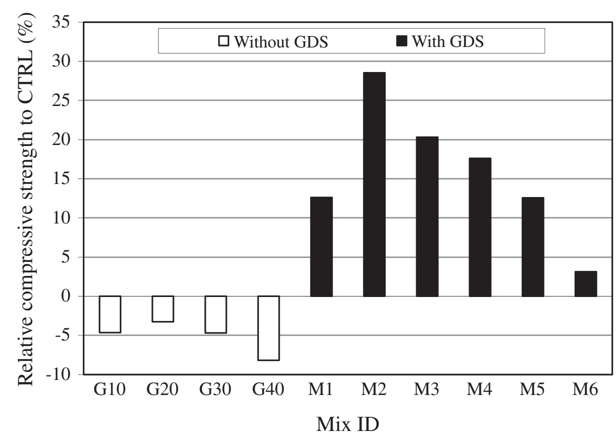

Fig. 5. Relative compressive strengths of GGBS mixtures with and without GDS to that of the CTRL mixture (all cured in the autoclave).

The best result was obtained with the M2 (30% GDS, 50% PC and 20% GGBS) mixture, which displayed 28% higher strength than the CTRL mixture cured in the autoclave. This result was likely due to the appropriate combination of cementitious materials used, which yielded an approximate C/S ratio of 0.88. It has been reported previously that the optimum combination of cementitious materials for high strength depends upon the fineness of the siliceous materials and the C/S ratio [31–33]. Generally, a C/S ratio less than or equal to unity is associated with high autoclave compressive strength. The results shown in Fig. 5 also reveal that M6 (30% GDS, 10% PC and 60% GGBS) had a strength comparable to that of the CTRL mixture. Thus, we concluded that ternary combination of PC, GDS and GGBS can be used with autoclave curing to reduce the amount of PC by up to 90% without negatively affecting the compressive strength of the mixture.

Fig. 6 presents the results of X-ray diffraction (XRD) analyses of selected mixtures (CTRL SC, CTRL AC and M1 AC). Two CH peaks were observed in the CTRL mixture cured under standard curing conditions. These peaks disappeared under autoclave curing conditions, and a new α-C_2SH peak appeared. The α-C_2SH component has a high C/S ratio and led to a decrease in the compressive strength of the hardened product. A peak of calcite was observed in CTRL SC mixture. This peak corresponding to carbonation reaction that

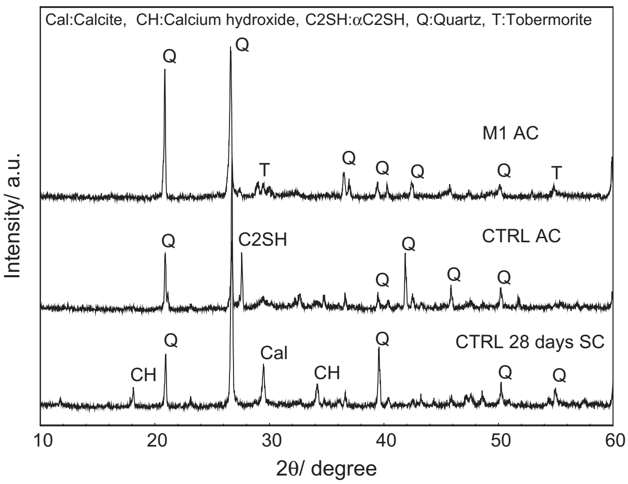

Fig. 6. XRD spectra of the CTRL mixture with standard curing, the CTRL mixture with autoclave curing and the M1 mixture with autoclave curing.

may have occurred between the CH hydrated from the PC and CO_2 from the air. The XRD results for the M1 (30% GDS and 70% PC) mixture cured in the autoclave indicate the formation of tobermorite, and CH peaks are absent. Tobermorite is generated by the reaction between the crystalline SiO_2 in the GDS and the CH liberated from the Portland cement compounds. The residual crystalline SiO_2 evidenced by XRD indicates unreacted SiO_2. The XRD results proved that the crystalline silica of ground dune sand has ability to prevent the formation of α-C_2SH and instead produce tobermorite.

4. Conclusions

The following conclusions can be drawn from the results of this experimental study:

1. The partial substitution of PC with GDS in binary blended cement did not significantly affect the fresh properties of the pastes or mortars. However, increasing the GGBS content led to an increase in the water required to achieve the normal consistency, but this had only a minor effect on the setting time.
2. As the content of GDS was increased in the binary mixtures, the compressive strength decreased with standard curing; however, with autoclave curing, the compressive strength was improved. The highest compressive strength was achieved with 30% of the PC replaced with GDS.
3. All of the binary and ternary blended mixtures developed greater compressive strength than the CTRL mixture when autoclaved. The combination of 30% GDS + 50% PC + 20% GGBS yielded the highest strength under autoclave curing conditions.
4. It is possible to reduce the PC content by up to 90% by incorporating GDS and GGBS in autoclave-cured mortar mixtures.
5. The compressive strength and XRD results confirmed that ground dune sand can be used as a partial cement replacement in precast concrete production using an autoclave curing system. This finding has significant implications for the sustainability and economy of concrete construction in countries with abundant supplies of natural dune sands.

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