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The effect of aggregates with high gypsum content on the performance of ultra-high strength concretes and Portland cement mortars

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HIGHLIGHTS

- Finding sand with a normal sulfate level is a major challenge in the Middle East.
- Natural sand with a high gypsum content was used in UHSC and PC mortar.
- UHSC with a compressive strength of 120–150 MPa was produced.
- The strength of steam cured UHSC enhanced with a higher gypsum content.
- PC mortar deteriorated with the presence of expansive ettringite.

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ABSTRACT

There is an increasing demand to ultra-high strength cement-based materials in the Middle East despite finding fine aggregates with a normal SO_3 level is a major challenge. This study was conducted to investigate the effect of increasing gypsum content of natural river sand on the properties of water and steam cured ultra-high strength concretes (UHSCs) and Portland cement mortars. All concrete and mortars were prepared with a w/c ratio of 0.197 and 0.440, respectively; yielding 28-day compressive strength ranges of 120–142 and 43–70 MPa, respectively. The experimental tests were expansion, compressive and splitting tensile strengths, and X-ray diffraction at varying ages. UHSC and mortar exhibited significant difference in resistance to internal sulfate attack. While UHSCs were not significantly affected by increasing gypsum content of sand, the Portland cement mortars deteriorated as seen by a drop in strength, a significant swelling, and the presence of expansive ettringite.

1. Introduction

1.1. Aggregates of high gypsum content

Most of the aggregates in the Middle East contain high amounts of sulfates, particularly gypsum. For instance, a survey of aggregate in the central and southern Iraq revealed that the most of sulfates in sand took the form of gypsum, which represents 95% of sulfates and the rest are sodium, magnesium, and potassium sulfates [1]. The SO_3 content in these aggregates is as high as 0.75–3% by weight.

Calcium sulfate, usually gypsum is added to the clinker at an optimum level to control the setting characteristics of cement. Gypsum reacts with C_3A to form primary ettringite. This type of ettringite happens in a plastic matrix and does not cause any damage. However, when the excessive amount of gypsum is present (from modern cement or gypsum-contaminated aggregates) [2], it will still exist within the hardened matrix and during curing of concrete the extra gypsum dissolves under water and SO_4 ions release. Then, the gypsum reacts with remaining C_3A and monosulfate hydrate according to Eqs. (1) and (2) to form delayed ettringite. The potential deteriorations of concrete caused by these reactions are described as internal sulfate attack.

$$\underset{\text{tricalcium aluminate}}{C_3A} + \underset{\text{gypsum}}{3C\bar{S}H_2} + \underset{\text{water}}{26H} \rightarrow \underset{\text{ettringite}}{C_6A\bar{S}_3H_{32}} \quad (1)$$

$$\underset{\text{monosulfate}}{C_4A\bar{S}H_{12}} + \underset{\text{gypsum}}{2C\bar{S}H_2} + \underset{\text{water}}{16H} \rightarrow \underset{\text{ettringite}}{C_6A\bar{S}_3H_{32}} \quad (2)$$

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Some international standards specify limits for SO_3 content in aggregate. For example, IQS 45 [3] allows 0.5% and 0.1% of SO_3 in fine and coarse aggregate, respectively. In the complimentary British Standard to BS EN 206-1 [4], it is reported that the maximum allowable SO_3 content in fine aggregate is 1%. However, due to the scarcity of aggregates with low sulfate contents in the Middle East region, many studies have been conducted to investigate the use of aggregate for conventional concrete and mortar with SO_3 content above the specified limits given by the international standards. In the study by Crammond [5] mortar made either with ordinary Portland cement or sulfate resistant Portland cement was incorporated with coarsely crystalline gypsum of up to 5% by weight of fine aggregate. According to the results, the allowable gypsum content in aggregates used in ordinary Portland cement mortars would not be much larger than 2.5% by weight of aggregate. For sulfate resistant Portland cement, this limit appeared to lie at a level of about 5%. Al-Rawi et al. [6] found that the effect of internal SO_3 on the compressive strength and expansion of concrete depended on the source from which it generated. The SO_3 from sand had less effect than that from cement and SO_3 generated from coarse aggregate had less effect as compared to that from sand. Kheder and Assi [7] investigated internal sulfate attack resistance of different concrete mixes with compressive strengths of between 15 and 75 MPa. In these mixes, sand with SO_3 content ranging from 0.5% to 2% was used. It was found that increasing the compressive strength of concrete resulted in enhancing its resistance to internal sulfate attack, and concrete mixes with a high strength (larger than 45 MPa) had a comparable expansion in water regardless of the sulfate content of sand. Atahan and Dikme [8] found that the use of different types of mineral admixtures such as silica fume, fly ash, and ground granulated blast furnace slag was a remedy for the problem of internal sulfate attack on mortars containing gypsum-contaminated aggregates from Iraq. Rodríguez et al. [9] utilized gypsum-contaminated fine recycled aggregates having 2.9% SO_3 in the mortars made with ordinary Portland cement or sulfate resistant Portland cement. Their results indicated that the expansion of both mortar types did not exceed the limit given in the literature, 0.1%.

Overall, the previous studies indicate that a certain amount of gypsum present in the aggregate can be tolerated for ordinary concrete and high strength concrete. However, higher gypsum content can be used with high strength concrete due to its lower permeability. This opens up the possibilities of using aggregate from the Middle East in the concrete with a very low permeability, UHSC which is the objective of the present study.

1.2. Ultra-high strength concrete

Ultra-high strength concrete (UHSC) is characterized by a higher strength, a much lower permeability and a denser microstructure as compared to the ordinary concrete. This is typically achieved by using silica fume, applying heat treatment, and using superplasticizers so that making possible to use a very low water/cement ratio. Apart from the pozzolanic reaction with lime, silica fume can fill the voids between the next larger class particles, cement leading to a dense material [10,11]. Moreover, the addition of silica fume densifies the packing in the interfacial transition zone, such that the porosity in this region is significantly reduced [12]. Superplasticizer also allows the cement grains to pack more uniformly, reducing the porosity of the paste, and thus improving density [13]. The effect of heat treatment, on the other hand, is to improve cementitious matrix because the pozzolanic reaction of silica fume is activated and the pore size is diminished due to the application of heat treatment [14,15]. Many investigators dealt with the behavior of UHSC after subjecting to various curing regimes such as steam curing and water curing. Yazıcı [16], for example, showed that the compressive strength of UHSC was higher under steam curing compared to water curing. However, no attention was given to the effect of curing methods on the strength of UHSC made with aggregate of high gypsum content which is the main source of aggregate in the Middle East.

1.3. Research significance

The present study aims at investigating the effects of using a fine aggregate with gypsum content higher than the normal limits in UHSC mixtures having a 28-day compressive strength exceeding 120 MPa. The other important parameter in this study is the influence of curing method, namely water curing and steam curing on the properties of UHSC with and without additional gypsum. The UHSC samples were tested for compressive strength, splitting tensile strength and expansion to monitor the composition-induced internal sulfate attack. The experimental results were supported by XRD analyses. In addition, the comparison was made between UHSCs and Portland cement mortars with respect to compressive strength, swelling, and XRD analysis because both of the materials contain no coarse aggregate. This would assist in a better understanding of the behavior of the UHSCs.

2. Experimental

2.1. Materials

Natural river sand (0–4 mm) and commercial quartz sand (0.6–1.2 mm and 1.2–2.5 mm) with a specific gravity of 2.66 and 2.65, respectively were used as fine aggregates. The natural crushed gypsum with the SO_3 content of nearly 38% was used as a partial substitution of the natural river sand to raise the original gypsum content of 0% to the desired contents of 1.68%, 3.66%, 7.61%, and 11.55%. Both crushed gypsum and natural river sand had a similar grading. A type F polycarboxylate-based superplasticizer (SP) in accordance with ASTM C494 [17] was used. Portland cement (CEM I 42.5 R) with C_3A content of 8.8% was used. Silica fume was also used in the present work. The properties of the cement and silica fume are presented in Table 1.

2.2. Mixture proportioning of UHSCs and Portland cement mortars

UHSC is typically characterized by a high level of silica fume and a very low water/cement (w/c) ratio [16]. The UHSC mixtures were designed with a constant w/c ratio of 0.197 and a constant silica fume content of 13% by weight of Portland cement. The high amount of silica fume is essential to optimize the filling performance and increase the compacted density of UHSC [15]. However, the hydration reaction of cement in UHSC is incomplete due to a very low w/c ratio and so the

Table 1
Properties of Portland cement and silica fume.

Item	Portland cement (PC)	Silica fume (SF)
SiO_2 (%)	19.69	90.36
Al_2O_3 (%)	5.16	0.71
Fe_2O_3 (%)	2.88	1.31
CaO (%)	62.12	0.45
MgO (%)	1.17	–
SO_3 (%)	2.63	0.41
K_2O (%)	0.88	1.52
Na_2O (%)	0.17	0.45
Cl (%)	0.0093	–
Loss on ignition (%)	2.99	3.11
Insoluble residue (%)	0.16	–
Free CaO (%)	1.91	–
Specific surface (m^2/kg)	394[a]	21,080[b]
Specific gravity	3.15	2.2
Compounds		
C_3S (%)	56.9	
C_2S (%)	13.8	
C_3A (%)	8.8	
C_4AF (%)	8.8	

[a] Blaine specific surface area.
[b] BET specific surface area.