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Sulfate-Induced Degradation in Concrete Exposed To Thermal Gradient

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Abstract **–** This study investigates the effects of external sulfate attack on concrete subjected to a thermal gradient. For this purpose, mortar beams measuring 40 × 40 × 160 mm were immersed in a 10% w/v $MgSO_4$ solution for up to 120 days. Three distinct temperature and humidity conditions, M2P, M5P and M5F, were simulated. The beams subjected to M2P and M5P conditions were partially submerged in the sulfate solution at 22°C and 50°C, respectively, whereas the M5F samples were fully immersed. Preliminary findings indicate that samples exposed to M5P experience the most severe physical degradation. Additionally, M5F samples exhibit the highest mass and volume gain, whereas M5P samples show the greatest loss in mass and volume after one month of exposure. In future studies, the mechanical and microstructural changes due to sulfate attack for the three exposure conditions will be investigated.

Keywords**:** Ettringite, Gypsum, Arid climate, Soret effect, External sulfate attack

1. Introduction

Sulfate-induced degradation in concrete is a well-known issue [1,2]. In arid climates like the Gulf region, limited rainfall, high evaporation rates, and elevated salinity levels contribute to the increased prevalence of external sulfate attacks [3]. Additionally, this region experiences extremely high ambient temperatures, particularly during summer, with values reaching or exceeding 50°C [4]. In structures where the interior is maintained at room temperature, this results in a thermal gradient developing within the concrete walls.

Several studies have examined the influence of thermal diffusion on chloride diffusion in concrete, revealing an acceleration of chloride ingress [5-7]. However, sulfate attack is a more complex process, necessitating a thorough investigation into the effects of thermal diffusion on external sulfate attack (ESA) in cementitious materials. Therefore, this study will investigate the effects of thermal diffusion on the mechanical properties and durability of cement mortars through a combination of experimental methods.

2. Experimental Program

Mortar beams measuring 40 × 40 × 160 mm were cast based on the mix design presented in Table 1. The samples were cured for 28 days before being exposed to a 10% w/v $MgSO_4$ solution under varying temperature and humidity conditions for up to 120 days. M2P Condition: 40 mm of the mortar beam was immersed in $MgSO_4$ solution at 22°C, while the remaining 120 mm remained above the solution at the same room temperature. This setup was designed to assess the effect of humidity gradient. M5P Condition: 40 mm of the beam was immersed in $MgSO_4$ solution at 50°C, while the exposed portion was subjected to air cooling at 22°C, evaluating the combined effect of humidity and thermal gradients on sulfate attack. M5F Condition: The entire beam was fully immersed in $MgSO_4$ solution at 50°C, examining the impact of isothermal elevated temperature on sulfate-induced degradation. In Figure 1, the detail of the experimental setup for sulfate exposure is presented.

Table 1. Mix design of the mortar samples

Material	O sample (kg/m^3)	SG sample (kg/m^3)
Type 1 cement	376	113
GGBS	-	244
SF	-	19
Dune sand	230	230
Crushed sand	706	706
Water	146	146
HWRA*	4.578	4.578

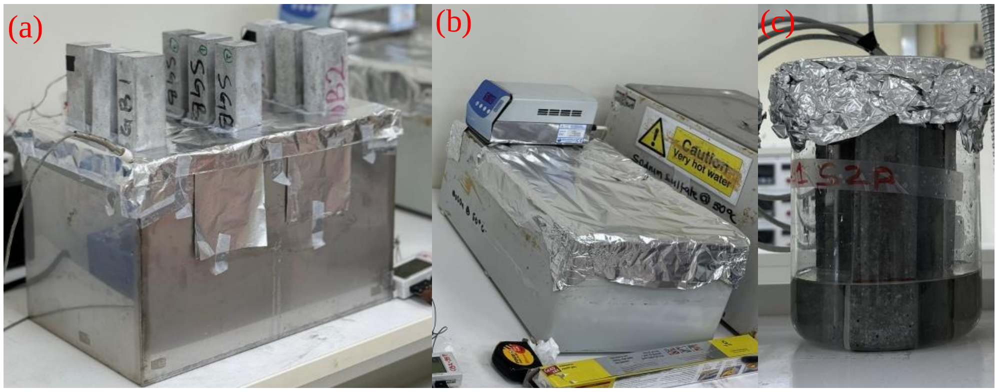

Fig. 1. Experimental setup for the sulfate exposure for the three exposure conditions. (a) M5P- to simulate the combined effect of thermal gradient and humidity gradient. (b) M5F- to simulate the effect of isothermal elevated temperature and (c) M2P- to simulate the effect of humidity gradient, on sulfate attack in concrete.

In the M5P samples, thermocouples were inserted at 60-, 100-, and 140 mm depth to monitor the temperature distribution within the sample. The temperature readings are presented in Figure 2.

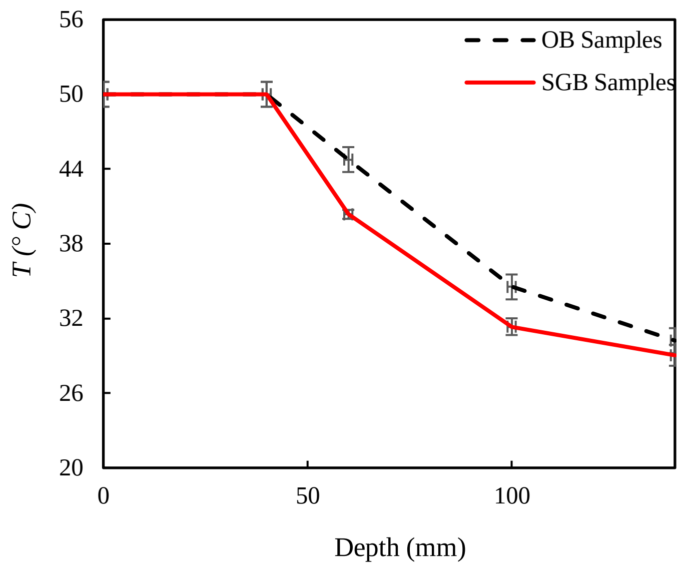

Fig. 2. Temperature distribution in the samples exposed to M5P condition.

2.1. Volumetric strain and mass change

The volumetric strain (%) and the percentage mass change of the beam samples were used as indicators for the extent of sulfate-induced degradation in the mortar samples. The dimensions of the beams were measured using digital vernier calliper with accuracy of 0.01 mm while the mass was weighed using the digital weighing balance with accuracy of 0.01 g.

2.2. Visual Inspection

A visual inspection of the mortar beams was performed to assess chemical deposition, defects, and crystallization under the three exposure conditions.

3. Results and discussion

In this section, the outcomes of the experimental work are presented. The volumetric strains and mass change of the samples after 1 month of sulfate exposure are presented. Also, the visual observations are presented.

3.1 Volumetric strain and mass change

After 1 month of exposure, the volumetric strain and mass change (%) of the three sample sets are displayed in Figure 3. From the results, the biggest increase in mass and volume change is found in the samples fully immersed in the sulfate solution while the greatest reduction in mass and volume change is found in the samples subjected to thermal diffusion. This is due to the varying degree of humidity in these samples.

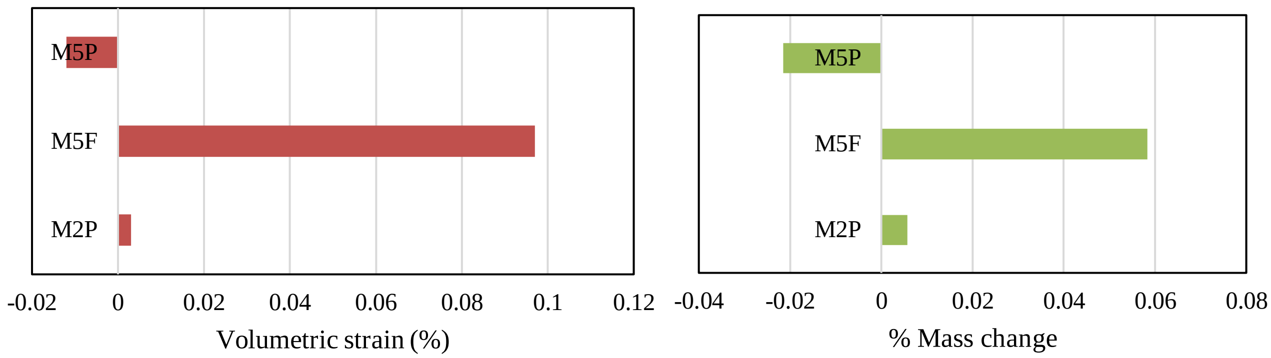

Fig. 3. Volumetric and mass change for the SG samples after 1 month of exposure.

3.2 Visual Inspection

Figure 4 reveals that the fully immersed sample (M5F) exhibited uniform physical degradation, accompanied by swelling and edge distortion. In contrast, the M2P sample showed only sulfate salt crystallization without significant physical damage. Meanwhile, the M5P sample experienced severe deterioration in the portion exposed to the sulfate solution, along with a substantial reduction in mortar mass. These observations underscore the influence of thermal and humidity gradients on the sulfate-induced physical degradation of mortar beams.

Fig.4. Visual inspection of the mortar beams after sulfate exposure (a) M2P, (b) M5P, and (c) M5F

4. Conclusion and future studies

In this study, the impact of thermal gradient on sulfate attack on mortar beams was investigated. To achieve this, three distinct temperature and humidity conditions, M2P, M5P and M5F, were simulated. The beams exposed to M2P and M5P conditions were partially submerged in the sulfate solution at 22°C and 50°C, respectively, while the M5F samples were fully immersed After 1 month of exposure, it was observed that the M5F samples had the highest mass and volumetric increase while the M5P samples had the highest mass and volumetric decrease. From visual inspection, it was observed that the greatest physical attack occurred in the M5P samples. This highlights the impact of thermal and humidity gradients on sulfate-induced degradation in mortar beams. In future studies, the changes in the electrical resistivity will be monitored. The compressive and the flexural strength of the samples will also be tested. Non-destructive techniques such as ultrasonic pulse velocity will be used to detect distortion to the samples such as cracks. More so, using microscopic tools such as XRD and SEM, the changes in the microstructure of the mortar samples will be analyzed. Enhancing the current understanding of factors influencing concrete structure degradation, particularly in warm climates, is essential. In the Middle East, and specifically in the UAE, interest in nuclear power plant (NPP) deployment is increasing. Therefore, it is critical to examine the interaction between concrete components in these NPPs and the UAE's unique environmental conditions. Furthermore, identifying the most severe exposure conditions contributing to sulfate-induced concrete degradation is vital for stakeholders in the nuclear energy sector.

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