Experimental Study on the Deterioration Mechanism of Sulfate Erosion of Desert Sand-Manufactured Sand Concrete under Dry-Wet Cycling Conditions

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Abstract. Concrete as a widely used construction material, exhibits particular importance in terms of durability under extreme environmental conditions, especially under the effects of wet-dry cycles and sulfate corrosion. This study focuses on concrete made from various proportions of desert sand and manufactured sand, investigating its durability and deterioration mechanisms under wet-dry cycles and sulfate corrosion. The experimental results indicate that wet-dry cycles induce the expansive effect of sulfate crystal formation, leading to concrete cracking and mass loss. The incorporation of an optimal amount of desert sand (DSDS25-MS75) enhances the particle gradation, improves concrete densification, reduces pore expansion, and minimizes crack connectivity, thus exhibiting superior resistance to corrosion. However, higher proportions of desert sand result in increased porosity, exacerbating structural deterioration. Nuclear magnetic resonance (NMR) analysis reveals that an optimal amount of desert sand helps inhibit changes in pore structure, thereby delaying the deterioration process. This study provides a theoretical basis for the durability of desert sand-manufactured sand concrete under extreme environmental conditions.

Keywords: desert sand; mechanism sand; wet-dry cycle; sulfate erosion; concrete durability; pore structure

1 Introduction

The durability of concrete under extreme environments is a significant issue [1], with wet-dry cycles and sulfate corrosion being the primary degradation factors, especially in arid or semi-arid regions. Wet-dry cycles, through changes in temperature and humidity [2], exacerbate the crystallization, dissolution, and migration of sulfate solutions within the concrete's pores, leading to volumetric expansion and crack propagation. Desert sand, as a low-cost and eco-friendly aggregate [3], has relatively poor bonding with the cement paste due to its rounded particle shape, resulting in lower resistance to corrosion. Manufactured sand, with its angular particles, enhances the mechanical properties and durability of concrete [4]. Therefore, the combined use of desert sand and

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manufactured sand holds promise for optimizing the particle gradation and improving the overall performance of concrete. Sulfate corrosion is closely related to the pore structure, crack propagation, and product accumulation in concrete [5,6], with wet-dry cycles accelerating this process [7]. Existing research has primarily focused on sulfate corrosion in conventional aggregate concrete [8], with relatively few studies on desert sand concrete, most of which focus on mechanical properties, particle gradation, and freeze-thaw damage [9,10]. The degradation characteristics and micro-mechanisms of desert sand-manufactured sand concrete under wet-dry cycles and sulfate corrosion have not been fully studied.

This study aims to investigate the degradation mechanisms of desert sand-crushed sand concrete under the combined effects of wet-dry cycles and sulfate attack. Accelerated laboratory experiments will be conducted to analyze the effects of various factors on the concrete's durability. In addition, micro-analysis techniques such as nuclear magnetic resonance (NMR) will be employed to reveal the degradation mechanisms. The research will provide a theoretical basis for the application of desert sand-crushed sand concrete in specialized environments and offer scientific support for improving its durability.

2 Experimental Program

2.1 Materials

The binder material used is P.O 42.5 ordinary Portland cement produced by the Qilian Mountain Cement Plant in Gansu Province. Coarse aggregates were sourced from a building materials plant in Gansu, with a moisture content of 0.15%, a particle size range of 5 to 20 mm, and a bulk density of 1650 kg/m^3. Fine aggregates include river sand (NS) from the Anning District of Lanzhou with a fineness modulus of 2.78 and moisture content of 3.3%, Tuff manufactured sand (MS) from a building materials company in Gansu with a fineness modulus of 2.95 and moisture content of 3%, and desert sand (DS) from the Tengger Desert area of Wuwei, Gansu, with a fineness modulus of 0.334 and moisture content of 0.14%. The admixture used is the SY-5 high-purity triterpenoid saponin-based air-entraining agent. Anhydrous sodium sulfate was used as the sulfate aggressor for corrosion.

2.2 Preparation of Test Pieces

The concrete mix with a strength grade of C30 was designed according to the Standard for Test Methods of Long-Term and Durability Performance of Ordinary Concrete (GBT50082-2009) [11]. The slump was ensured to be ≥150 mm, with the admixture accounting for 0.015% of the binder mass, and a water-to-binder ratio of 0.42. Desert sand (0%, 25%, 50%, 75%, 100%) and manufactured sand (100%, 75%, 50%, 25%, 0%) were mixed in equal proportions to replace river sand, forming desert sand-manufactured sand concrete. A replacement ratio of 0% was used as the river sand concrete (DSDS0-MS0) reference group, with the mix proportions as shown in Table 1. Specimens of two sizes, 100 mm × 100 mm × 100 mm and 100 mm × 100 mm × 400 mm, were cast for subsequent testing. The specimen numbering is explained using the example of DSDS75-MS25, where "DS" refers to the wet-dry cycling-sulfate attack test, "DS75" indicates a 75% desert sand content, and "MS25" indicates a 25% tuff manufactured sand content.

Table 1. Concrete mixing ratios

Specimen number	Desert sand rate/%	MS (kg/m^3)	DS (kg/m^3)	Natural coarse aggregate(kg/m^3)
DSDS0-MS0	0	0.0	0.0	1178.0
DSDS0-MS100	0	580.0	0.0	1178.0
DSDS25-MS75	25	435.0	145.0	1178.0
DSDS50-MS50	50	290.0	290.0	1178.0
DSDS75-MS25	75	145.0	435.0	1178.0
DSDS100-MS0	100	0.0	580.0	1178.0

2.3 Wet-dry-salt Cycling Test

According to the standard [11], concrete specimens were removed during the first 4 days of the curing period and immersed in clean water at 20±2°C. After immersion, the specimens were placed in specimen boxes for wet-dry cycling tests. Specimens were placed in the specimen boxes, and a 5% sodium sulfate solution by mass was added until the liquid level was 50 mm above the specimen's top surface. The specimens were soaked for 6 hours and then oven-dried at 80±5°C for 3 hours. After drying, the specimens were cooled for 1 hour, completing one wet-dry sulfate attack cycle. A total of 200 cycles were conducted. Every 25 cycles, the mass and dynamic elastic modulus of 100 mm × 100 mm × 400 mm specimens were measured. Surface morphology observations and nuclear magnetic resonance (NMR) testing were conducted every 100 cycles. After completing the sulfate wet-dry cycles, 100 mm × 100 mm × 100 mm cube specimens were vacuum-saturated in water for 24 hours. Once saturation was achieved, surface water was wiped off before conducting the NMR test. The detailed experimental procedure is illustrated in Fig. 1.

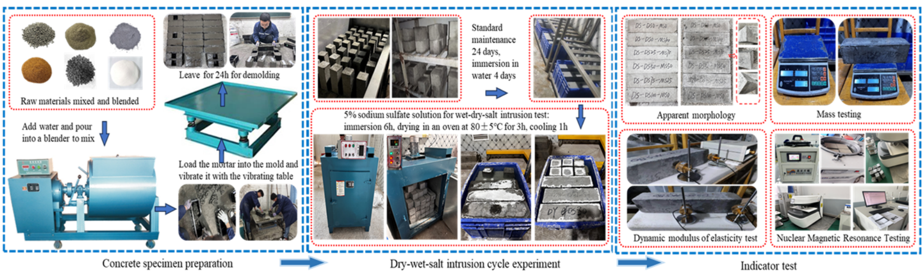

Fig. 1. Flow chart of dry-wet-salt intrusion test of desert sand-manufactured sand concrete

3 Test Results and Analysis

3.1 Apparent Damage Analysis

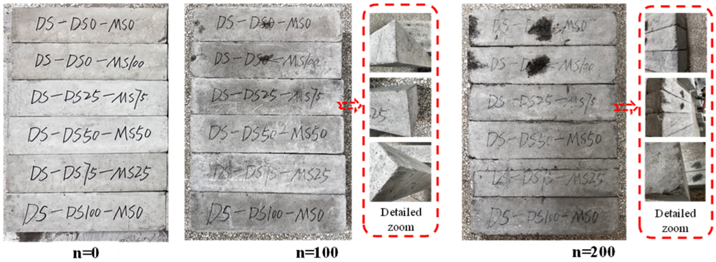

Fig. 2. Apparent morphology of DS-MS concrete during dry-wet-salt intrusion

In a 5% Na_2SO_4 solution, under the effects of wet-dry cycling, the apparent damage of concrete specimens with varying desert sand contents exhibited characteristic changes, as shown in Fig. 2. In the early stage (0 to 50 cycles), the surface of the specimens showed only a few microcracks and slight delamination, with damage mainly concentrated in the surface layer. This is due to the migration of SO_4^{2-} ions in the pores and the crystallization pressure caused by moisture evaporation. As the number of cycles increased, the differences in damage performance became more pronounced: DS-DS0-MS0 and DS-DS0-MS100 specimens only had a few microcracks on the surface, DS-DS25-MS75 performed the best with almost no damage, while specimens with 50% to 100% desert sand content showed more fissures and slight local mortar delamination. After 200 cycles, the damage further intensified. Notably, the 25% desert sand specimens exhibited only small pores and corner damage.

The damage mechanism of wet-dry cycling-sulfate attack is primarily caused by the crystallization expansion effect of sulfate solution during periodic infiltration and evaporation. SO_4^{2-} ions accumulate in the surface pores, and the evaporation of moisture leads to crystallization expansion, which in turn causes cracking and mortar delamination [5]. Due to the absence of significant volumetric expansion, the damage progresses slowly and is mainly concentrated in the surface layer, with minimal impact on the deeper structure [6]. The erosion of the salt solution also leads to salt precipitation, further accelerating surface degradation, but the overall structural integrity remains intact.

3.2 Mass Loss Analysis

Wet-dry cycling-sulfate attack is a multi-field coupled degradation environment, and its damage to desert sand- manufactured sand concrete is primarily manifested in the migration process of the salt solution, where repeated salt dissolution and crystallization cause microcrack expansion and structural damage, ultimately leading to a decline in material performance. Experiments have shown that the mass loss process of desert sand- manufactured sand concrete in the wet-dry cycling-sulfate attack can be divided into three stages: mass growth, mass loss, and accelerated mass loss [7]. As shown in Fig. 3, in the early stage, the concrete pores adsorb the salt solution and fill the pores, leading to mass growth; in the intermediate stage, crystallization pressure triggers the expansion of microcracks and deterioration of the pore structure, resulting in mass loss; in the later stage, cracks deepen, surface spalling occurs, and aggregate loss accelerates the mass loss.

Concrete with different mix proportions exhibited significant differences in mass loss rates. DS-DS0-MS0, due to its favorable particle size distribution and lower porosity, showed minimal mass loss, while DS-DS0-MS100, with higher porosity, experienced greater mass loss. DS-DS25-MS75 exhibited a lower mass loss rate [7], but an excessive amount of desert sand increases the moisture demand, resulting in increased porosity and reduced resistance to erosion. The number of wet-dry cycles and the salt solution environment have a significant impact on the rate of mass loss. As the number of wet-dry cycles increases, the erosion time extends, the degradation effect accumulates, and the expansion effect of salt crystals intensifies the structural damage to concrete.

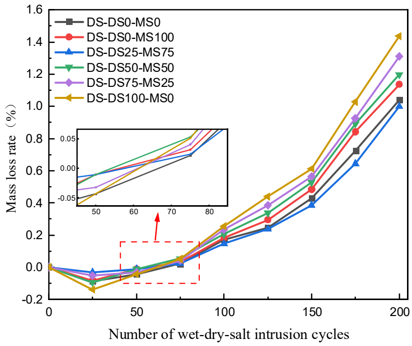

Fig. 3. DS-MS concrete quality loss rate change curve

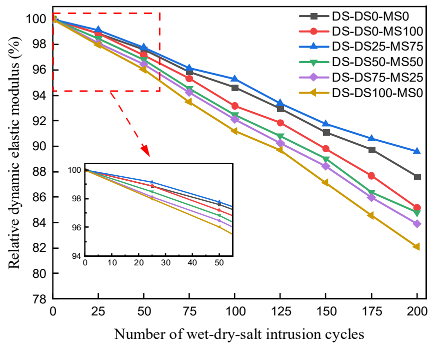

Fig. 4. Variation curve of relative dynamic elastic modulus of DS-MS concrete

3.3 Relative Dynamic Elastic Modulus Analysis

The relative dynamic elastic modulus is an important indicator for evaluating crack propagation in concrete. In a wet-dry cycling-sulfate attack environment, the relative dynamic elastic modulus of all desert sand-manufactured sand concrete specimens gradually decreases with the increase in corrosion time, exhibiting a staged pattern, as shown in Fig. 4. In the early stage (0-75 cycles), sulfate ions penetrate through capillary pores and microcracks, and the repeated processes of dissolution, crystallization, and expansion pressure accelerate crack propagation, causing a rapid decline in the modulus. In the intermediate stage (75-125 cycles), cracks gradually connect, the expansion pressure diminishes, and the sulfate crystallization forms a "blocking effect," slowing down the crack development, which leads to a deceleration in the rate of modulus reduction. In the later stage (125-200 cycles), cracks further expand and connect, and the accumulation of expansive corrosion products destabilizes the internal structure [5], leading to a decrease in overall stiffness and crack resistance, resulting in a rapid reduction in dynamic elastic modulus [8].

The ratio of desert sand to manufactured sand significantly affects the relative dynamic elastic modulus of concrete. The rough and angular particles of manufactured sand enhance the bonding performance between cement paste and aggregates, improving concrete stiffness and durability. Specimens with a high proportion of manufactured sand (DS-DS0-MS100) show better durability, while those with a high desert sand content (DS-DS100-MS0) exhibit accelerated crack propagation and significant degradation due to poor interfacial performance [10]. A moderate amount of desert sand (25%) improves the particle grading and enhances the internal structure density of concrete [3], effectively reducing salt penetration and the rate of crack propagation. The specimens with 25% desert sand (DS-DS25-MS75) exhibit the best relative dynamic elastic modulus and resistance to degradation. The influence of the desert sand and manufactured sand ratio is mainly reflected in the interfacial bonding performance and the stability of the microstructure.

3.4 Analysis of Pore Structure

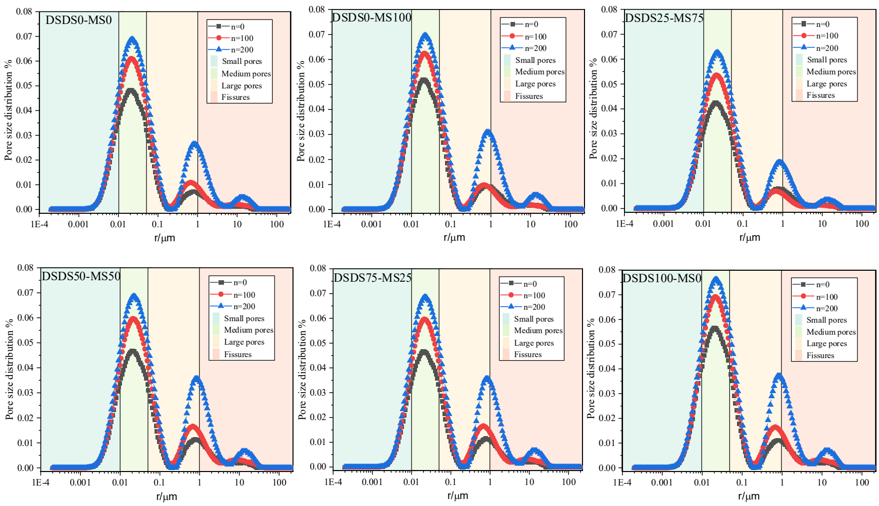

Fig. 5. Pore size distribution curve of DS-MS concrete

Nuclear magnetic resonance (NMR) testing is used to analyze the evolution of the micro-porous structure within concrete, focusing primarily on the liquid-containing pores. The T_2 spectrum from NMR testing reflects the pore size distribution within the concrete. The pores in concrete can be categorized into four types: small pores (r < 0.01 μm), medium pores (r = 0.01 ~ 0.05 μm), large pores (r = 0.05 ~ 1 μm), and fissures (r > 1 μm) [3]. The transverse relaxation T_2 spectrum obtained through NMR analysis can be converted into a pore size distribution curve [12], with the pore size distribution curves for different concrete samples shown in Fig. 5.

Under wet-dry cycling-sulfate attack, the pore size distribution curves of desert sand-manufactured sand concrete exhibit three distinct peaks, corresponding to different pore size ranges. As the number of wet-dry cycles and sulfate attacks increases, the proportion of internal pores in the concrete gradually increases [13] , and the peaks of the curves rise, indicating changes in the pore structure. Before the wet-dry cycling-sulfate attack (Cycle 0), the internal pores in all specimens were few. After 100 cycles, there was a significant increase in small and medium pores in the specimens. After 200 cycles, all three peaks significantly increased, particularly the second and third peaks, indicating that as the corrosion intensified, the pore structure gradually interconnected, leading to a decline in the overall concrete performance [8].

This trend reflects the significant impact of wet-dry cycling-sulfate attack on the pore distribution of desert sand-manufactured sand concrete, especially in the later stages of corrosion. As the proportion of desert sand increases, the increase in porosity becomes more pronounced, resulting in poorer resistance to corrosion, particularly in specimens with a high desert sand content (DS-DS75-MS25, DS-DS100-MS0), where the pore structure degrades most severely, and crack expansion accelerates, leading to the worst corrosion resistance. The incorporation of desert sand significantly impacts the pore structure and corrosion resistance of concrete. A moderate amount of desert sand (25%) can optimize the pore structure and enhance the durability of concrete [14] , whereas excessive desert sand content significantly reduces its corrosion resistance.

4 Conclusions

This study reveals the degradation mechanism of desert sand-manufactured sand concrete under wet-dry cycling and sulfate attack. The results indicate that:

DS-MS concrete shows surface micro-cracks and delamination, with slow, limited damage. Sulfate expansion mainly affects the surface, with little impact on the deeper structure.

The mass loss follows a three-phase process: an initial increase, followed by a decrease, and then an accelerated decline. The incorporation of a moderate amount of desert sand (25%) optimized the aggregate gradation, significantly reducing the mass loss rate, whereas higher proportions of desert sand intensified degradation.

The relative dynamic modulus of elasticity showed a staged decline over the erosion cycles. Manufactured sand concrete exhibited higher stiffness, while concrete with high desert sand content was more prone to degradation.

NMR analysis demonstrated that higher desert sand content exacerbated the formation of large pores and fissures, leading to structural degradation. The incorporation of a moderate amount of desert sand effectively enhanced the concrete's resistance to corrosion.

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