Degradation of Mechanical Properties and Quantification of Meso-structural Damage in Mortar after Chemical Erosion (Postprint)

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Abstract

This study investigates the deterioration of mechanical properties and the evolution of micro- and meso-structural damage in mortar specimens under different hydrochemical environments, and explores the mesoscopic mechanisms underlying mechanical property degradation. The results indicate that the pre-peak plastic deformation of specimens increases after chemical corrosion. The stronger the chemical corrosion effect of the solution on the specimens, the greater the plastic deformation, which exhibits distinct temporal stage characteristics. The change in plastic deformation of specimens after corrosion indirectly reflects the degree of corrosion by the chemical solution on mortar specimens. A non-destructive measurement method is proposed to calculate the porosity of mortar specimens during different corrosion periods, and a new damage variable is established based on changes in porosity. The study finds that the consistency between the chemical damage degree of mortar specimens and their physico-mechanical parameters is relatively significant. This demonstrates that it is reasonable to quantitatively describe the chemical damage degree of the micro- and meso-structure of specimens and the evolution of their physico-mechanical characteristics with chemical damage using a damage variable established based on the secondary porosity generated by chemical corrosion.

Full Text

Salt Solution Attack Induced Mechanical Property Degradation and Quantitative Analysis Method for Evolution of Meso-structure Damages of Mortar

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ABSTRACT

The evolution of meso-structure in mortar significantly affects its macroscopic mechanical properties. This study investigates the mechanisms of mechanical property degradation and the evolution of corrosion-induced meso-structure damages in mortar after immersion in different salt solutions. Experimental results demonstrate that after salt solution corrosion, the plastic deformation of mortar increases; the stronger the corrosion attack, the larger the plastic deformation. However, this is an obvious time-dependent process. Thus, the degree of plastic deformation may serve as an indicator of the corrosion degree of mortar. A method based on nondestructive inspection was proposed to predict the variation of mortar porosity versus corrosion time, and a new damage parameter was established. The present study reveals that after immersion in salt solutions, the corrosion attack-induced damage degree of mortar is closely related to its physical and mechanical parameters, which proves that the proposed method for quantitative analysis of meso-structure damage evolution is reasonable.

KEY WORDS inorganic non-metallic materials, mortar specimen, chemical erosion, meso-chemical damage variable, plastic deformation

1. Introduction

With rapid economic development, environmental pollution has become increasingly severe. Various corrosive ions in rainwater and groundwater cause complex aqueous chemical corrosion of concrete, mortar, and other materials during service, seriously affecting the durability of civil engineering structures. This issue has attracted considerable attention from both engineering and academic communities, becoming a frontier fundamental topic in civil engineering.

In recent years, extensive research has been conducted worldwide on the effects of aqueous chemical environments on cement-based materials, yielding numerous results [1-17]. Using microscopic detection instruments such as EDAX, scanning electron microscopy, and SEM, researchers have found that the corrosion effects of acidic chemical solutions on mortar and similar materials are highly complex [1-4]. Xie et al. [5,6] simulated acid rain effects on mortar specimens through spray and cyclic immersion methods, discovering that acid rain corrosion causes mineral component loss in mortar specimens, reducing their strength. The degradation degree of specimen strength exhibits a binary linear relationship with the ratio of mineral components CaO and SO_3/CaO. Acid rain effects result from the combined action of H^+ and $SO_4{}^{2-}$, where H^+ erosion causes dissolution corrosion of hydrated products in mortar, while $SO_4{}^{2-}$ [incomplete thought in original]. Huo et al. [7,8] studied the effects of acidic chemical solutions on the physical properties and wave velocity characteristics of mortar specimens. Ning et al. [9] investigated the influence of different chemical solutions on the strength and stress-strain relationships of mortar specimens. Zheng [10] conducted experimental studies on the strength and deformation characteristics of mortar specimens after corrosion by different chemical solutions and proposed a calculation model for the strength of chemically corroded mortar specimens. Yang et al. [11] examined the mass and strength properties of mortar specimens under different acidic conditions and analyzed the effects of mineral admixtures and $SO_4{}^{2-}$ ion concentration on acid resistance. However, these studies primarily focused on macroscopic mechanical and physical properties of cement mortar under chemical solutions, without investigating structural changes after corrosion.

References [12,13] examined the chemical corrosion damage effects of acidic chemical solutions on the surface structure of mortar specimens. Yang et al. [12] studied the acid resistance of different cement mortars and analyzed the corrosion mechanisms of acidic solutions on mortar specimens, finding that chemical corrosion changes the surface structure of specimens, increases porosity, and ultimately degrades mechanical properties. Chen et al. [13] simulated acid rain effects on mortar surface chemical corrosion damage through dry-wet cycling tests, revealing that acid rain corrosion is a chemical process progressing from the surface inward. Song et al. [14] studied the mechanism of dilute sulfuric acid erosion on mortar and established an acid consumption rate erosion model based on boundary layer theory. However, few studies have focused on the meso-structure damage effects and quantification of mortar specimens after chemical corrosion. Chemical solution corrosion manifests microscopically as changes in composition and internal meso-structure, leading to increased porosity, while macroscopically 主要表现为 varying degrees of degradation in mechanical parameters. The degradation of macroscopic mechanical parameters is the external manifestation of internal meso-structure damage changes, while internal damage is the intrinsic cause of macroscopic mechanical parameter degradation. Based on this understanding, this study investigates the effects of different acidic conditions, different concentrations of sulfate solutions, and different chemical compositions on the mechanical properties of mortar specimens. A nondestructive testing method is proposed to calculate the porosity of mortar specimens during different corrosion periods, and the influence of chemical corrosion on meso-structure is analyzed. Simultaneously, a chemical damage variable is established based on porosity changes after chemical corrosion to explore quantitative research methods for chemical damage to the meso-structure of mortar specimens.

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2. Experimental Methods

Testing Equipment

The experiments utilized a WDT-1500 multifunctional material testing machine, consisting of five components: axial loading system, confining pressure loading system, lateral shear system, acoustic wave detection system, and computer control and measurement system. The maximum axial force is 1500 kN, maximum confining pressure is 80 MPa, and the measurement ranges for axial and radial deformation are 0-10 mm and 0-5 mm, respectively.

A RSM-SY5 acoustic wave detector was used to test longitudinal wave velocity with a transducer frequency of 50 kHz. Test data were recorded by an RSM-SY5 transient digital signal recording and processing instrument.

A PHS-3C pH meter measured solution pH values with a measurement range of pH 0-14, -1400 to +1400 mV, and automatic polarity display. The concentrations of dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}, Fe^{2+}) ions in solutions were measured using a TAS-990 atomic absorption spectrophotometer.

Mortar Specimen Preparation

The mass ratio of mortar specimen components was cement (c): sand (s): water (w) = 1:2:0.5. The cement was Shaanxi Qinling P.O32.5 Portland cement, and the sand was from the Chan River in Xi' an. Raw materials were washed and dried, and strict control of sand particle size gradation was implemented to ensure aggregate uniformity. The particle size gradation and weight ratio of sand aggregates were: f_1 (0.16-0.315 mm): f_2 (0.315-0.63 mm): f_3 (0.63-1.25 mm): f_4 (1.25-2.50 mm) = 5%:30%:40%:25%. Specimens were cast in one-time molding into cylindrical shapes with 50 mm diameter and 100 mm length, demolded after 24 hours of curing, then cured in a curing box (20°C, 90% humidity) for 28 days before natural air drying.

Solution Preparation

To analyze and discuss the effects of different acidity/alkalinity, different sulfate concentrations, and different chemical compositions on mortar mechanical properties, the following solutions were prepared: 0.01 mol/L Na_2SO_4 and 0.01 mol/L $NaHCO_3$ solutions; Na_2SO_4 solutions with concentrations of 0.01, 0.1, and 0.5 mol/L to analyze concentration effects; and 0.01 mol/L Na_2SO_4 solutions adjusted to pH values of 1, 3, 7, and 9 using HNO_3 and NaOH reagents to measure pH effects. Distilled water at pH=7 was used as a control.

2. Results and Discussion

Starting from the beginning of the tests, the pH values of different aqueous chemical solutions and the concentrations of dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+} and Fe^{2+}) ions were measured after 240 days of immersion to obtain the variation patterns of physical parameters of different aqueous chemical solutions with corrosion time.

2.1 Variation of Solution pH Values The variation patterns of pH values for various chemical solutions after 240 days of immersion are shown in [Figure 1: see original paper]. Regardless of the chemical solution type, the pH values exhibited weak alkalinity with increasing chemical corrosion time between water and rock. In a relatively closed chemical environment, the solution pH tended toward self-equilibrium over time. The reason is that hydrogen ions in the solution gradually decreased with immersion time. The Portland cement used in the tests hydrolyzes to generate minerals such as dicalcium silicate, which produce large amounts of calcium hydroxide after hydration. Calcium hydroxide is also responsible for the alkaline nature of the solution. Additionally, some hydration products such as calcium aluminate hydrate are alkaline, ultimately causing the chemical solutions to exhibit alkalinity after immersion.

2.2 Variation Patterns of Chemical Solution Physical Parameters The variation patterns of dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}+Fe^{2+}) ion concentrations in various chemical solutions after 240 days of immersion are shown in [Figure 2: see original paper]-[Figure 5: see original paper]. As seen in Figures 2-5, the concentrations of dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}+Fe^{2+}) ions all increased after a series of hydrochemical interactions between water and rock. Under the same conditions, the stronger the acidity of the chemical solution, the more intense the chemical reaction between water and rock, and the greater the dissolved ion concentration; the greater the $SO_4{}^{2-}$ concentration, the greater the dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}+Fe^{2+}) ion concentrations.

[Figure 4: see original paper] shows that within the same chemical corrosion period, the concentrations of dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}, Fe^{2+}) ions in $SO_4{}^{2-}$ solution are all higher than in $HCO_3{}^{-}$ solution. This indicates that different solution chemical compositions have different corrosion effects on mortar, and under the same conditions, the corrosion effect of $SO_4{}^{2-}$ on mortar is stronger than that of $HCO_3{}^{-}$.

As seen in [Figure 5: see original paper], after immersion in neutral chemical solutions, the concentrations of dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}, Fe^{2+}) ions also increased. This demonstrates that even pure water interacts with rock through not only physical actions but also more complex chemical actions. Neutral chemical solutions also have certain corrosive effects on mortar, primarily dissolution. The ion concentrations dissolved in $SO_4{}^{2-}$ solution and the corresponding mechanical parameter degradation degrees are both greater than those in pure distilled water, indicating that the corrosion effect of $SO_4{}^{2-}$ ions on mortar is stronger than that of pure distilled water.

2.3 Effects of Chemical Corrosion on Mortar Mechanical Parameters Microscopically, chemical corrosion manifests as changes in specimen composition and internal meso-structure, reflected in increased porosity; macroscopically, it 主要表现为 degradation of mechanical parameters. The degradation of macroscopic mechanical parameters is the external manifestation of internal meso-structure damage changes, while internal damage is the intrinsic cause of macroscopic mechanical parameter degradation. This indicates that mechanical parameter degradation is closely related to internal damage. The stronger the corrosion effect of the solution on mortar specimens, the higher the concentrations of dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}+Fe^{2+}) ions, and the greater the degradation degree of the corresponding mechanical parameters.

Uniaxial compression experiments were conducted on mortar specimens immersed for 60, 120, and 240 days, with results listed in .

The strength parameters of chemically corroded mortar specimens degraded to varying degrees, with obvious time-dependent stages. The peak strain of corroded mortar specimens increased and grew with chemical corrosion time, indicating a trend of transformation from brittleness to ductility. The main reason is that after a series of hydrochemical interactions between chemical solutions and mortar specimens, the composition and internal meso-structure changed, leading to increased porosity and making specimens softer and more vulnerable. Simultaneously, with prolonged corrosion time, the corrosion became more complete, ultimately causing the deformation characteristics to show a trend toward ductility.

Comparative analysis of [Figure 2: see original paper]-[Figure 5: see original paper] and shows obvious consistency between the degradation degree of mortar mechanical parameters and the ion concentrations dissolved in solutions. That is, the greater the corrosion effect of the solution on mortar specimens, the greater the concentrations of dissolved Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}+Fe^{2+}) ions, and the greater the degradation degree of specimen mechanical parameters.

In neutral environments, the mechanical parameters of mortar specimens decreased to varying degrees, while the concentrations of Ca^{2+}, Mg^{2+}, and Fe (Fe^{3+}+Fe^{2+}) ions in solutions increased. However, the reduction amplitude was smaller compared to the natural state, indicating that neutral environments have certain corrosive effects on mortar specimens, primarily dissolution. The ion concentrations dissolved in ${SO_4}^{2-}$ solution and the corresponding mechanical parameter degradation degrees were both greater than those in pure distilled water, demonstrating that the corrosion effect of ${SO_4}^{2-}$ on mortar is greater than that of pure distilled water. Comparative analysis shows that under the same conditions, the ion concentrations dissolved in ${SO_4}^{2-}$ solution and the degradation degrees of specimen mechanical parameters are both greater than those in ${HCO_3}^{-}$ solution, indicating that the corrosion effect of ${SO_4}^{2-}$ ions on specimens is stronger than that of ${HCO_3}^{-}$ ions.

After immersion in chemical solutions, the deformation characteristics of mortar specimens show a trend of transformation from brittleness to ductility. The average values of pre-peak plastic deformation of mortar specimens after hydrochemical solution corrosion are listed in [19,20].

As seen in , the plastic deformation of mortar specimens after chemical solution immersion increased compared to the natural state. Simultaneously, plastic deformation increased with chemical corrosion time. Based on the above analysis, the more severe the corrosion of mortar specimens by chemical solutions, the greater the plastic deformation.

Comparing with [Figure 6: see original paper]-[Figure 7: see original paper], there is a close correspondence between plastic deformation and peak strain of chemically corroded mortar specimens, i.e., plastic deformation increases with increasing peak strain. The reason is that chemical corrosion changes the mineral composition and internal meso-structure of specimens, causing varying degrees of porosity increase. This increased porosity is compacted during the compression stage of the stress-strain curve, increasing the compaction segment, relatively reducing the elastic stage, and making the yield stage increasingly obvious, leading to increased peak strain. Another part of the increased peak strain comes from plastic deformation generated by the corrosion-softening effect of the solution on mortar specimens.

In summary, the degradation degree of mortar mechanical parameters is closely related to internal chemical damage. The more severe the corrosion of specimens by chemical solutions, the greater the damage to the internal meso-structure, the higher the degradation degree of mechanical parameters, and the greater the peak strain and plastic deformation. Therefore, the pre-peak plastic deformation of corroded specimens can be used to indirectly reflect the damage degree of the internal meso-structure of mortar specimens.

2.4 Variation Patterns of Mortar Specimen Porosity and Longitudinal Wave Velocity Direct measurement of specimen porosity in the laboratory is difficult. Numerous studies have found that the elastic wave velocity of specimens is very sensitive to internal porosity changes—the more developed the internal pores and the greater the damage, the smaller the longitudinal wave velocity. Therefore, longitudinal wave velocity can be used to indirectly determine porosity. The longitudinal wave velocity of the same specimen can be tested at different chemical corrosion time periods without causing damage, thereby obtaining porosity at different time periods.

According to Fermat' s principle, let n be the porosity of the specimen after chemical corrosion for t(d) days, be the longitudinal wave velocity of the specimen after chemical corrosion for t(d) days (m/s), be the longitudinal wave velocity of the specimen particle skeleton (m/s), and _f be the longitudinal wave velocity of the solution in the specimen pores (m/s).

From equation (1), we can derive _f/(_f), _f/(However, the prerequisite for applying equations (1)-(3) is that can be treated as a constant throughout the chemical corrosion process, i.e., chemical corrosion does not cause qualitative changes in rock properties. For specimens corroded by the same chemical solution, the properties of the solution in the internal pores are identical, meaning _f is a constant. Substituting these two constant values and _f into equation (3) allows calculation of a and b. Therefore, for equation (2), the specimen porosity is only a function of its longitudinal wave velocity.

Since the chemical solutions are relatively dilute, the longitudinal wave velocity _f of the solution in the specimen pores can be considered as the solution' s longitudinal wave velocity, i.e., _f = 1500 m/s; under dry conditions, the pores inside the specimen are filled with air, i.e., _f = 334 m/s. Based on literature [18] and the specific gravity bottle method, the particle density of the specimen was measured. Considering these factors comprehensively, = 5300 m/s was adopted.

The longitudinal wave velocity can be measured nondestructively at different chemical corrosion time periods. The porosity of specimens during corresponding corrosion periods was calculated using equations (2) and (3), with results listed in .

As seen in [Figure 8: see original paper] and [Figure 9: see original paper], with increasing specimen porosity, the longitudinal wave velocity shows varying degrees of decrease, and there is obvious consistency between specimen porosity and longitudinal wave velocity. Therefore, the change in longitudinal wave velocity of mortar specimens can be used to reflect changes in internal porosity and the degree of internal meso-structure damage after chemical corrosion. This also demonstrates that the experimental data obtained in this study are reasonable and reliable.

3.1 Damage Variable

Comparing , , and [Figure 10: see original paper], the internal pores of specimens after chemical corrosion all increased, and the damage degree of the internal meso-structure intensified. Chemical corrosion caused varying degrees of damage to the meso-structure of specimens, leading to increased internal porosity. A damage variable was defined based on porosity changes to reflect the chemical damage degree of the internal meso-structure caused by chemical corrosion.

$D = 1 - (n_0/n)$

where n_0 is the porosity of mortar specimens before corrosion, and n is the porosity after corrosion.

Macroscopically, the physical and mechanical parameters of specimens showed degradation phenomena. The damage degree of specimens under different hydrochemical solutions was calculated using equation (4), with results listed in . The relationships between physical and mechanical parameters and the chemical damage variable of chemically corroded mortar specimens are shown in [Figure 11: see original paper]-[Figure 13: see original paper].

Regression analysis of [Figure 11: see original paper]-[Figure 13: see original paper] yielded:

$\mathrm{U} \ = 0.185$
$\ = 0.2242 \ln$
$\mathrm{e}^{-70}.^{922} = 4.2481 \ln$
$= 60.7277$
$= -909.091 + 1.3933 + 22.5077 + 22.273$
$= 0.9437$
$= 0.9383$
$= 0.9789$
$= 0.9223$
$= 0.9304$

As seen in equation (5), the internal damage degree of specimens after chemical corrosion increased. Meanwhile, with increasing damage, the peak strength and elastic modulus gradually decreased, while peak strain, plastic strain, and the rate of change of longitudinal wave velocity after corrosion all showed varying degrees of increase. This further proves that the cumulative effect of chemical solution corrosion on specimens over time leads to degradation of physical and mechanical parameters.

[Figure 14: see original paper]-[Figure 15: see original paper] show the relationship curves between ion concentrations dissolved in chemical solutions and the damage variable. As seen in , , and [Figure 14: see original paper]-[Figure 15: see original paper], the stronger the corrosion effect of the solution on specimens, the greater the concentrations of dissolved ions, the greater the internal damage, leading to increased porosity and decreased longitudinal wave velocity, and resulting in greater degradation of mortar mechanical parameters. These results demonstrate that there is a close relationship between physical parameters or chemical parameters of solutions and mechanical parameters of specimens.

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4. Conclusions

1. Different chemical solutions have different corrosion effects on mortar. After corrosion, the strength parameters of mortar specimens degrade to varying degrees, with obvious time-dependent stages. However, peak strain and plastic deformation increase with corrosion time, indicating a trend of transformation from brittleness to ductility.
2. Under the same conditions, the more severe the corrosion of specimens by chemical solutions, the higher the concentrations of dissolved ions, the greater the internal damage, leading to increased porosity and decreased longitudinal wave velocity, and resulting in greater degradation of mortar mechanical parameters. This demonstrates that there is a close relationship between physical/chemical parameters and mechanical parameters.
3. After chemical corrosion, there is a close relationship between plastic deformation and peak strain of mortar specimens, i.e., plastic strain in-

creases with increasing peak strain. Chemical corrosion leads to increased pre-peak deformation, partly from compression deformation due to increased porosity, and partly from plastic deformation caused by corrosion-softening effects.

4. There is obvious consistency between porosity and longitudinal wave velocity of specimens after chemical corrosion. The change in longitudinal wave velocity can reflect the degree of internal meso-structure damage. Using nondestructive methods to test the longitudinal wave velocity of the same mortar specimen at different corrosion periods can yield porosity at different time periods.
5. There is obvious consistency between the chemical damage degree of mortar specimens and their physical and mechanical parameters, indicating that using a porosity-based damage variable to quantitatively describe the chemical damage of internal meso-structure is reasonable.
6. After chemical corrosion, the peak strength shows an exponential relationship with the damage variable, while elastic modulus and plastic deformation show linear relationships, and peak strain and longitudinal wave velocity change rate show logarithmic relationships with the damage variable.

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