Construction and Building Materials 144 (2017) 541–551

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Influence of the initial moist curing time on the sulfate attack resistance of concretes with different binders

Zengqi Zhang [a], Qiang Wang [a,*], Honghui Chen [a], Yuqi Zhou [b]

[a] Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] China Construction First Group Construction and Development Co., Ltd., Beijing 100102, China

HIGHLIGHTS

- GGBS enhances the sulfate attack resistance of concrete even under insufficient moist curing condition.
- Moist curing for at least 7 days is necessary for the concrete containing fly ash.
- The sulfate attack resistance of concrete is less sensitive to the moist curing time at lower W/B ratio.

ARTICLE INFO

Article history:
Received 22 November 2016
Received in revised form 18 March 2017
Accepted 30 March 2017
Available online xxxx

Keywords:
Sulfate attack
Compressive strength loss rate
Moist curing regime
Mineral admixture
Water/binder ratio

ABSTRACT

The influence of the initial moist curing time on the resistance to the sulfate attack of concretes with different binders and at different water/binder ratios was studied by determining the compressive strength and the chloride ion permeability of the concrete before sulfate attack, the compressive strength after sulfate attack, and the microstructure of the corroded concrete matrix. The results illustrate that both the crystallized sodium sulfate and ettringite formed due to invaded sulfate are the principal expansion sources of the concrete subjected to the sulfate attack environment. Both the additions of fly ash and ground granulated blast furnace slag (GGBS) tend to significantly reduce the permeability and enhance the sulfate attack resistance of concrete on the premise of sufficient moist curing. The enhancing effect of GGBS is greater than that of fly ash on the sulfate attack resistance of concrete with each initial moist curing regime. In the case of insufficient moist curing for 3 or 7 days, the compressive strength loss rate of concrete containing fly ash is close to that of the plain cement concrete, indicating that the addition of fly ash makes little contribution to the enhancement of the sulfate attack resistance of concrete. Though the enhancing effect of GGBS on the sulfate attack resistance of concrete decreases with the decrease of moist curing time, the compressive strength loss rate of the concrete containing GGBS is about half of that of the plain cement concrete. The sulfate attack resistance of concrete is less sensitive to the moist curing time at lower water/binder ratio.

1. Introduction

The service life of the concrete structures is closely related to the service environment. The concrete structure often suffers corrosion of harmful ions in the environment of ocean or salt lake, such as chloride ion and sulfate ion, which definitely results in great degradation of the mechanical properties and durability of concrete. The negative effects of sulfate ion on the microstructure and the mechanical properties of concrete have been widely reported [1–3]. Song et al. [4] researched the damage evolution of the Poisson's ratio of concrete under sulfate attack and found that the Poisson's ratio of concrete at water/binder ratio of 0.4 increased 10.14% after immerged in sulfate solution for 285 days. Liu et al. [5] studied the deterioration of seismic performance of concrete and found that the strength of the sulfate attack concrete was more sensitive to the strain rate. Chen et al. [6] reported the effect of the sulfate ion concentration and the water/cement ratio on the damage evolution of concrete due to the sulfate attack by ultrasonic technique and found that the micro-pore size significantly affected the damage evolution of concrete. Liu et al. [7] found that sulfate ions tended to accelerate the chloride corrosion of reinforcing steels in the case of the concomitant presence of chloride and sulfate ions.

The sulfate attacks can be divided into two manners: chemical and physical attack, both of which lead to the degradation of the

* Corresponding author.
E-mail address: w-qiang@tsinghua.edu.cn (Q. Wang).

http://dx.doi.org/10.1016/j.conbuildmat.2017.03.235
0950-0618/

properties of concrete. The sulfate ion penetrated into the concrete and diffused in the micro pores of the matrix and reacted with the ions inside the pore solution, resulting in the delayed ettringite formation (DEF) [8–11]. Generally, the solid ettringite is formed in the micro voids of the cement matrix due to the reaction of sulfate ion and aluminate [12]. In the meanwhile, the sulfate salt crystals grow inside the micro pores of concrete from the supersaturated solution [13]. The formation of the delayed ettringite and the sulfate salt crystal increased the expansion force inside the cement matrix after it growing and touching the boundary of the pores.

The permeation of the sulfate ion into the concrete matrix is one of the most important processes during the sulfate corrosion. Thus the total porosity and the connectivity of the micro pores have a great influence on the deterioration degree of the properties of sulfate attacked concrete since they are closely connected with the permeability of the concrete. So the measures which make much more compact matrix, such as lowering the water/binder ratio (W/B) and replacing part of cement with pozzolanics, can improve the sulfate attack resistance of concrete [14]. Siad et al. [15,16] researched the effect of water/binder ratio and the nature of mineral admixtures on the long-term performance of the sulfate attacked concrete and found that the addition of natural pozzolan or fly ash improved the sulfate resistance of self-compacting concrete. Sumer [17] found that the improving effect of Class C fly ash on the sulfate resistance of concrete was much more significant than that of the Class F fly ash. The addition of GGBS was found to enhance the sulfate resistance of concrete containing Class F fly ash [18]. Karakurt et al. [19] found that the addition of fly ash and GGBS reduced the delayed ettringite formation and thus improved the sulfate resistance of concrete since the sulfate resistance of concrete was closely related to the formation of gypsum and delayed ettringite. Ye et al. [20] reported that less gypsum and ettringite were found in the mortar with GGBS than that of the Portland cement mortar after exposed to 10% Na_2SO_4 salt spray. Al-Amoudi [21] summarized the beneficial impacts of mineral admixtures on the sulfate attack resistance of concrete: reduce the production of gypsum by the consumption of $Ca(OH)_2$; reduce the C_3A content due to the dilution effect; densify the hardened matrix by the formation of secondary C-S-H gel; hinder the formation of secondary ettringite by covering the alumina-rich phases with the secondary C-S-H gel. The physical and chemical effect of the mineral admixtures on the microstructures reduced the permeability of the concrete, decreased the mass diffusion rate of the sulfate ion, reduced the formation of ettringite and sulfate salt crystals and thus enhanced the sulfate resistance performance.

The curing regimes and the curing duration affect the macroscopic and microscopic properties of the concrete. Jia et al. [22] found that the initial curing period influenced the carbonation of concrete and the adequately moist curing decreased the large pores and interconnected channels. Presuel-Moreno [23] found that the curing regime influenced the evolution of the resistivity of the concrete. Wet curing at least for the initial 7 days was found to be necessary for the pozzolanic cement concrete to stimulate the pozzolanic reactivity of the mineral admixtures [24]. The cracking of the concrete due to the drying shrinkage in the concrete structure generally results in the degradation of the mechanical properties and durability. The permeability increased due to the cracking of the concrete promotes the mass diffusion of the harmful ions and thus aggravates the durability problems, i.e. sulfate erosion and chloride ion penetration. Maslehuddin et al. [25] reported the effect of curing methods on shrinkage and the corrosion resistance of concrete and found that the wet curing time required for the concrete containing silica fume was longer than that of the plain cement concrete. Proper moist curing methods tend to reduce the early age shrinkage deformation and the evaporation rate is decreased with the prolonging of the curing duration [26].

Based on a review of the literature, the initial moist curing time affects the microstructures and thus affects the durability of concrete, e.g. the resistance to carbonation and chloride penetration. In many places, a large number of concrete structures are built in the salty soil region and cannot be sufficiently cured at early ages due to the severe construction conditions and lack of water. It can be deduced that insufficient moist curing has adverse effect on the sulfate attack resistance of concrete. The early hydration properties and sensitiveness to initial moist curing of composite binders are quite different from those of plain cement. The sulfate attack resistance of the concrete with high content of mineral admixture in the case of insufficient moist curing deserves to be investigated.

In this research, the influence of the initial moist curing times (3, 7 and 28 days) on the sulfate attack resistance of the plain cement concrete and the concrete containing fly ash or GGBS was studied. The sensibility of the properties of concretes with different water/binder ratios (0.45 and 0.35) to the initial moist curing time was also discussed.

2. Experimental

2.1. Raw materials

P.I 42.5 Portland cement conforming to Chinese National Standard GB 175 (equivalent to European CEM I 42.5) was utilized in this study. The specific surface areas of cement, fly ash, and ground granulated blast furnace slag (GGBS) are 341 m^2/kg, 358 m^2/kg and 430 m^2/kg, respectively. The chemical compositions of the cement and the mineral admixtures determined by XRF are shown in Table 1.

2.2. Mix proportions

The mix proportions of plain cement concrete and the concretes containing fly ash and GGBS are provided in Table 2. Concretes with two different water/binder ratios (0.35 and 0.45) were prepared. Two cement replacement ratios were adopted: 37.5% and 50%.

2.3. Test methods

Concrete cubes with the dimension of 100 mm $\times$ 100 mm $\times$ 100 mm were prepared. Three kinds of early curing conditions were adopted and provided in Table 3. After curing for 28 days, the concrete specimens were exposed to the sulfate salt solutions under drying-wetting cycles. In the meanwhile, the concrete specimens which were further cured under standard curing condition were employed as the reference samples. Thaulow and Sahu [27] found that sodium sulfate was the most commonly salt that attacked the concrete structures in the salty regions. The performance degeneration of the concrete immersed in sodium sulfate solution was more obvious than that of the concrete exposed to other sulfate salt solutions [28–30]. So 5% sodium sulfate was employed in this study. The drying-wetting test was conducted according to the Chinese National Standard GBT50082-2009 "Standard for test methods of long-term performance and durability of ordinary concrete". The specimens were immersed in 5% sodium sulfate solution for 15 h at 20 °C, naturally air dried for 1 h, oven-dried for 6 h at 80 °C and then naturally cooled for 2 h. A complete wetting-drying cycle was accomplished in 24 h.

The compressive strengths and the resistance to the chloride ion penetration of the concrete at 28 days under different curing conditions were measured. The resistance of the concrete to the chloride ion penetration was evaluated by determining the charge passed according to ASTM C 1202. The compressive strengths of