Construction and Building Materials 235 (2020) 117463

Contents lists available at ScienceDirect

Construction and Building Materials

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

Change on shear strength of concrete fully immersed in sulfate solutions

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HIGHLIGHTS

- The time-dependent evolution of concrete shear strength components due to sulfate attack was investigated.
- Sulfate-induced degeneration on concrete specimens may change the shear dilation and contact friction.
- The failure criterion of concrete specimens under direct shearing was altered after long-term sulfate exposure.

ARTICLE INFO

Article history:
Received 24 March 2019
Received in revised form 12 October 2019
Accepted 2 November 2019

Keywords:
Direct shear strength
External sulfate attack (ESA)
Shear-friction
Shear dilation

ABSTRACT

Sulfate-caused deterioration on concrete is principally evaluated by measuring the variation of uniaxial compressive strength and longitudinal expansion at different exposure ages. The evolution of concrete shear strength and its components over exposure period in such a sulfate-rich environment is overlooked. This study aims to characterize the time-dependent evolution of concrete shear strength and its components and to identify the possible microscopic deterioration mechanisms corresponding to these macroscopic properties changes under sulfate-exposure conditions. For this study, direct shear tests on concrete specimens subjected to different sulfate-exposure periods were conducted, where the effects of three water-to-binder ratios (w/b of 0.38, 0.45 and 0.52) and four sulfate-exposure periods (0, 3, 6 and 9 months) were considered. Results indicate that the shear strength and its components of concrete specimens under direct shearing are significantly influenced by external sulfate attack (ESA). For example, shear dilation of concrete specimens under direct shearing diminishes over sulfate-exposure period. However, friction component has a slight increase at the early exposure period in sulfate solutions, followed by a rapid drop at the later exposure period. In addition, the failure criterion of concrete specimens is found to be transformed from the bi-linear Mohr-Coulomb (M-C) before exposure to the linear M-C criterion after exposure in sulfate solutions.

1. Introduction

Sulfate attack on concrete material is a crucial degeneration mechanism in the case of concrete structures/members directly contact with sulfate-contaminated soils or groundwater [1–10]. Sulfate reaction products such as ettringite and gypsum and thaumasite have been regarded as the ringleader who should be responsible for this durability pathosis on concrete [11–22]. This deterioration mechanism primarily causes macroscopic expansion, spalling and loss of strength on concrete materials [23–28]. Thus, changes in length, mass and uniaxial compression strength were often measured using laboratory test methods on mortar/concrete samples, to analyze the resistance of concrete materials to sulfate attack. The effects of sulfate-exposure on these physical and mechanical properties of concrete materials are hence well-documented by numerous publications and ongoing researches around the world. However, "shear" in concrete, including shear strength and its components, is also vital since large amount of concrete members/structures suffer from shear loading [29,55]. In rare cases the evaluation of degeneration grade of concrete due to sulfate attack was carried out by measuring the associated shear strength. Such dearth of related information made the impacts of sulfate-exposure on shear responses of concrete unclear.

Reportedly, the shear strength components of concrete materials comprised hydrated cement paste-aggregate adhesion, contact friction, shear dilation, and cement-aggregate interlock [30]. When no normal stress perpendicular to the shear plane was applied, the pure shear strength was often determined using the Iosipescu tests

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https://doi.org/10.1016/j.conbuildmat.2019.117463
0950-0618/

[31], four-point or three-point bending tests [32,33], direct shear tests [34–37] and push-off tests [38]. In these cases, the friction is believed to be somewhat weak, and the main contributions to shear strength are adhesion and interlocking. If sulfate ions have the chance to invade into concrete, the cementitious pastes in weak areas such as interfacial transition zone (ITZ) should be first targeted [39]. Once these cementitious pastes are defeated, the cement paste-aggregate adhesion and aggregate interlocking structures can be significantly influenced. In this way, the macro-mechanical properties were believed to be reduced under such attacking. Haufe and Vollpracht [40] found that the tensile strength of concrete exposed to sulfate attack was reduced. They explained that this degeneration in tensile strength was attributed to the form of ettringite and gypsum. The response of concrete under shear is clearly different from that under tensile stress, since shear-friction should be enhanced if normal stress and roughness increase. Brueckner et al. [41] investigated the influence of thaumasite sulfate attack (TSA) on skin friction at the concrete/clay interface, and found that the skin friction was enhanced due to the form of thaumasite at interface near to concrete. By their analysis, this enhancement was due to the local expansive pressure caused by sulfate product thaumasite. This pressure can miraculously act as a normal stress perpendicular to shear plane (interface), to prominently mobilize the friction at these areas. Meanwhile, this chemical process also improved the roughness of interface, further enhancing the friction force along these failure areas. Recently, Pastor et al. [42] in their paper on skin friction change due to sulfate attack also reported the similar findings to Brueckner et al. [41]. This positive effect of thaumasite-type attack on concrete provided an interesting research topic in this field, since previous reports or standards always recommended the engineers that concrete structures/members or concrete/soil interface should be carefully designed to withstand the thaumasite-type attack. In addition, shear dilation is more prominent in compact structures compared to loose ones [30,37]. Once concrete/shotcrete was attacked by sulfate ions, looseness of microstructure was inevitable since the hardened cement pastes were destroyed. Meanwhile, shear dilation should be suppressed when a high vertical load was applied. However, relevant reports concerning the evolution of shear dilation and friction of concrete due to sulfate attack are rare.

Wong et al. [30] studied the shear strength components of concrete under direct shearing, where the mobilization of each component under direct shearing was presented. Three normal stress conditions were adopted in that paper, thus it was difficult to duly investigate the associated failure envelope. Sonnenberg et al. [43] conducted direct shear tests to study the shear strength of concrete. They proposed a bi-linear Mohr-Coulomb (M-C) failure envelope to describe the relationship between peak shear stresses and normal stresses. They attributed the existence of gradient point on bi-linear envelope to the change of failure mode. However, most of these tests were carried out on concrete specimens non-exposed to sulfate environments. Although many reports concluded that concrete strength can be significantly influenced by external sulfate attack (ESA), the shear failure mode and failure criterion of sulfate-exposed concrete under direct shearing are rarely published. Shear strength components of cement-based materials comprise hydrated cement paste-aggregate adhesion, contact friction, shear dilation, and cement-aggregate interlock along the shear surface under direct shearing [30]. According to the classical literature concerning "*shear-friction*", the shear strength can be described by a conbination of three different load carrying mechanisms: adhesion or cohesion, shear-friction and shear reinforcement [50–54,56,57]. The adhesion/cohesion component is originated by chemical bond connections, also termed as "*aggregate interlocking*". The second term, shear-friction, is related to the contribution due to the longitudinal relative slip and is influenced by the surface roughness and the normal stress at the shear interface. The last one, shear reinforcement, is related to the contribution of the flexural resistance of the shear reinforcement crossing the interface. This one was also known as "*dowel action*". Clearly, the former two terms are the main concern in this study since no reinforcement was added. However, the alteration of these components due to sulfate attack remains unclear.

Lack of theoretical information or inadequate understanding on engineering science problem may cause poor design and even high cost of repair. The evolution of shear strength components of concrete due to sulfate attack is vital for underground engineering such as tunnel linings and defect repair. It is also important to well understand the sulfate-damage mechanism on cement-based materials from aspect of direct shear tests. For this experimental research, the direct shearing tests [37] are performed on concrete specimens exposed to ESA, to evaluate the evolution of shear strength and its components over exposure period. The evolution of shear responses of sulfate-exposed concrete under current direct shearing condition would be explained from both macro- and micro-scales in this study.

2. Experimental program

2.1. Materials and specimen preparation

Three concrete mixtures were prepared by varying the water-to-binder ratios (w/b), using a mix of ordinary Portland cement (P.O 42.5), low-alkali accelerator, superplasticizer, fine/coarse aggregates and local tap water in Chongqing, China. All used materials conformed to the requirement of Chinese standards [44–47], as listed in Tables 1 and 2. In order to match the practice, all mixtures were prepared near to a working face in a site construction of tunnel project (*Hongyan Village Station of Chongqing Rail Transit Line 9*). The mixture design proportion was also taken from the construction organization (*China Construction Tunnel Corp.*) in *China State Construction Engineering Corporation (CSCEC)*, as illustrated in Table 3. The mixtures were moulded in slab with dimensions of 450 mm × 350 mm × 120 mm using dry-mix method, and were then cut into standard cubic specimens with a length of 100 mm [48,49]. These specimens were ready for testing after curing for 28 days in standard condition (temperature of 20 ± 2 °C and relative humidity (RH) of 98%) [37,48,49].

2.2. Sulfate exposure test

After curing, concrete specimens were fully immersed in 5 wt.% by weight sodium sulfate solutions (at ambient temperature) for

Table 1
Materials information of cement and accelerator.

	Cement	Accelerator
Chemical composition		
SiO_2 (%)	19.38	14.63
Al_2O_3 (%)	6.47	18.79
Fe_2O_3 (%)	3.12	4.14
CaO (%)	56.96	32.73
MgO (%)	1.23	0.65
SO_3 (%)	2.05	0.27
TiO_2 (%)	0.38	1.52
P_2O_5 (%)	0.45	0.31
f-CaO (%)	0.82	
Alkali (%)	1.15	10.41
Cl^- (%)	0.006	0.29
Loss of ignition (%)	4.09	
Physical properties		
Density (g/cm^3)	3.07	
Blaine fineness (cm^2/g)	3341	