Construction and Building Materials 166 (2018) 23–34

Contents lists available at ScienceDirect

Construction and Building Materials

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

Resistance of recycled aggregate concrete containing low- and high-volume fly ash against the combined action of freeze–thaw cycles and sulfate attack

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HIGHLIGHTS

- The effects of CRCA replacement level under the combined F–T and sulfate attack are analyzed.
- The effects of LVFA and HVFA under the combined F–T and sulfate attack are analyzed.
- The durability was more affected by the FA content than by the CRCA replacement level.
- Interaction between F–T and sulfate attack to concrete with RCA and FA is discussed.
- NMR and XRD analysis of concrete subjected to F–T cycles in sulfate solutions are conducted.

ARTICLE INFO

Article history:
Received 31 July 2017
Received in revised form 15 January 2018
Accepted 16 January 2018
Available online 22 February 2018

Keywords:
Recycled aggregate concrete
Coarse recycled concrete aggregates
High-volume fly ash
Low-volume fly ash
Freeze–thaw cycle
Sulfate attack
Microstructure

ABSTRACT

The present study investigated the effect of the combined action of freeze–thaw (F–T) cycles and sulfate attack on the resistance of concrete containing low-volume fly ash (LVFA) and high-volume fly ash (HVFA) made with coarse recycled concrete aggregates (CRCAs). Concretes with a water–binder ratio of 0.50 containing fly ash (FA; LVFA and HVFA) and CRCA (i.e., 0%, 20%, 50% and 100% also by weight) as a replacement for coarse natural aggregates (CNAs) were exposed to water, 5% sodium sulfate solution and 5% magnesium sulfate solution under F–T cycles. The performance, including residual compressive strength, relative dynamic modulus of elasticity and concrete microstructure, was evaluated after being subjected to certain F–T cycles in sulfate solutions. Results indicated that the resistance of the concrete mixtures to the combined F–T cycles and sulfate attack increased with the increase in CRCA content as CNA replacement. Compared with the concrete without FA, the LVFA-based concrete showed excellent improvement in the resistance to the combined action of F–T cycles and sulfate attack; however, the HVFA-based concrete had an adverse effect on the resistance. Concrete deterioration was attributed to the interaction between F–T and sulfate attack. Moreover, the resistance of LVFA- and HVFA-based concretes against the combined F–T and sulfate attack increased during the entire test when the concretes were subjected to F–T cycles in 5% sodium sulfate solution. The sulfate attack exerted more positive effects than negative on the F–T cycles. However, the resistance of LVFA- and HVFA-based concretes against the combined F–T and sulfate attack increased during the initial F–T cycles and then decreased in the 5% magnesium sulfate solution. The 5% sodium sulfate solution produced similar improvements in the F–T resistance of the LVFA- and HVFA-based concretes, whereas the 5% magnesium sulfate solution evidently reduced the F–T resistance of the concrete with HVFA than that with LVFA.

1. Introduction

Breakthrough developments in the construction industry have resulted in the increasing rate of construction and demand for concrete for new buildings. Thus, finding an eco-friendly method for handling construction and demolition (C&D) waste is necessary. Recycled concrete aggregate (RCA) can serve as a partial substitute

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https://doi.org/10.1016/j.conbuildmat.2018.01.084

for virgin aggregates in new concrete production and provide a good and promising solution for handling C&D waste and saving construction materials [1]. A previous study [2] showed that several sulfate-rich soils and salt lakes are scattered in Japan, the Arabian Gulf region, Northwest China, Southern California in the USA, Australia and the Alpine areas. In these regions, the durability of concrete structures has deteriorated, and their service life has decreased due to damage from freeze–thaw (F–T) cycles and sulfate attacks. Therefore, studying the effects of the damage of F–T cycles and sulfate attacks on recycled aggregate concrete (RAC) structures can improve the sustainable production of concrete in these regions.

Several studies on the production and characterisation of recycled aggregates have been conducted [3–6]. The mesostructure of RAC is more complex than that of conventional concrete given the presence of mortar adhering to the surfaces of RCA particles [7]. Furthermore, the presence of microcracks and residual cement paste results in high porosity, low density and high water absorption of RCA [8].

F–T damage diminishes the durability and service life of concrete structures. Medina et al. [9] found that concrete F–T resistance increases with the increase of RCA content; the improved performance is due to the high mechanical property of RAC and the intrinsic properties of the new aggregate. Gokce et al. [10] proposed a method to assess the frost susceptibility of coarse RCAs (CRCAs) that originated from air-entrained and non-air-entrained concrete; they found that the performance of concrete produced with air-entrained RCA is slightly better. Bogas et al. [11] concluded that incorporating fine RCAs (FRCAs) is not detrimental to F–T resistance, particularly in the internal F–T resistance of concrete. Tuyan et al. [12] reported that the weight change of RAC mixtures exposed to F–T cycles increases when the water–binder (w–b) ratio of the mixture and CRCA content is increased. Alan et al. [13] found that the durability of RAC is at least equal to that of concrete manufactured with virgin aggregates, considering that the replacement aggregate and treatment prior to batching are carefully selected.

Several studies on the sulfate attack of concrete produced with RCA can be found in literature. Boudali et al. [14] concluded that mixtures with CRCA and FRCA exhibit better sulfate resistance than those with natural aggregates and natural pozzolana. Zega et al. [15] evaluated the performance of RAC made with different RCA contents and exposed to sulfate soil and they found that the RAC and natural aggregate concretes have the same compressive strength. Lee et al. [16] suggested that 50% and 100% replacement levels of FRCA result in increased or similar resistance to $MgSO_4$ and Na_2SO_4 attacks. Corral-Higuera et al. [17] evaluated the durability of reinforced RAC structures exposed to a high-sulfate solution and found that increasing the supplementary cementitious materials contributes to the increased resistance to RAC sulfate attack.

Jiang et al. [18] investigated the properties of conventional concrete subjected to F–T cycles in sulfate solutions. They concluded that the coupled action of sulfate attack and F–T cycles severely accelerates the deterioration of concrete structures. The properties of plain concrete and steel–fibre-reinforced concrete (SFRC; with water–cement ratios of 0.44, 0.32 and 0.26) subjected to F–T cycles in 5% sodium sulfate solution were investigated. Results showed that the properties of SFRC are superior to those of plain concrete, and the decline in the relative dynamic modulus of elasticity (RDME) of SFRC is significantly slower than that of plain concrete [19]. Yang et al. [20] systematically investigated the effects of sulfate attack and F–T cycles on concrete microstructure through advanced test methods, such as water absorption method, air void analysis, X-ray diffraction (XRD) and scanning electron microscopy. Their experimental results indicated that F–T damage is the dominant factor in sulfate attack and F–T alternation tests. Wang et al. [2] investigated the durability of concrete containing fly ash (FA) and silica fume (SF) against combined F–T and sulfate attacks. Their experimental results indicated that the replacement level of 25% FA and 5–8% SF by weight results in significant improvements in the resistance of concrete against the combined F–T and sulfate attacks.

Low and high replacement levels of FA have been used in several investigations [21–23]. On the basis of replacement levels, concrete containing FA of up to 30% and greater than 50% is termed as low-volume FA (LVFA) and high-volume FA (HVFA) concrete, respectively [24]. These forms of concrete have gained popularity worldwide due to their excellent benefits in terms of durability, sustainability, cost effectiveness and other long-term performance aspects [25–27]. Hemalatha and Ramaswamy [28] reported that the engineered FA concrete with cement replacement of up to 60% is an attractive alternative in terms of both durability and strength. Kurad et al. [29] suggested that using FA in RAC is advisable from the strength and environmental impact points of view. Khodair and Bommareddy [30] revealed that the high replacement of cement with FA and slag produces an adverse effect on the compressive strength; however, it results in improved resistance to chloride diffusion.

Investigations about concrete resistance on F–T cycles and sulfate attack have been conducted in the concrete science and engineering communities. However, to the best of the author's knowledge, information about the resistance of LVFA- and HVFA-based concrete mixtures made with RCA to the combined F–T cycles and sulfate attack is not available. Thus, this study aimed to evaluate the resistance of LVFA- and HVFA-based concrete mixtures made with various replacement levels of coarse natural aggregates (CNAs) with CRCA to the combined F–T cycles and sulfate attack. In this study, the RDME and compressive strength of concrete subjected to sulfate attack and F–T cycles in water and sulfate solutions were investigated. Specifically, nuclear magnetic resonance (NMR) and XRD were used to explore the F–T cycle and sulfate attack mechanism at a microscopic level. Furthermore, the influences of the FA and CRCA replacement levels and sodium sulfate types under the combined action of F–T cycles and sulfate attack were analysed.

2. Experimental details

2.1. Materials, mixture proportions and specimen details

The chemical composition and properties of the general-use Portland cement and Class F FA are listed in Table 1. The fine aggregate was Weihe River sand with a fineness modulus of 2.54. Natural gravel with a maximum size of 20 mm was used as CNA. CRCA was produced through a crushing process with a jaw crusher. CRCA samples with diameters of 5–20 mm were selected after the

Table 1
Chemical composition and properties of the cement and FA.

Contents	Cement	FA
SiO_2 (%)	21.45	49.57
Al_2O_3 (%)	6.45	30.31
CaO (%)	61.5	5.67
Fe_2O_3 (%)	3.09	7.01
MgO (%)	1.21	0.83
K_2O (%)	1.38	1.36
Na_2O (%)	0.25	0.43
SO_3 (%)	2.01	1.25
Loss on ignition (%)	4.05	3.48
Specific gravity (g/cm^3)	3.15	2.31
Specific surface area (cm^2/g)	3412	3955