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Effects of parent concrete and mixing method on the resistance to freezing and thawing of air-entrained recycled aggregate concrete

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HIGHLIGHTS

- We study the frost resistance of air-entrained recycled aggregate concrete (ARAC).
- The effects of four parent concretes and three mixing approaches are investigated.
- The failure mechanism of ARAC after freezing and thawing is established.
- This is done on the basis of a mesostructural analysis of the test samples.

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ABSTRACT

We elucidated the effects of the parent concrete and mixing approach used on the freezing/thawing resistance of air-entrained recycled aggregate concrete (ARAC). Three non-air-entrained concretes and one air-entrained concrete were used to prepare recycled coarse aggregate (RCA) samples. Three mixing approaches were also investigated. The frost resistances of the ARAC samples produced using an RCA obtained from the non-air-entrained concrete with high strength as well as the air-entrained one were close to that of conventional concrete. The mixing approach used had no effect on the frost resistance. A possible mechanism for the failure of ARAC is proposed.

1. Introduction

With the rapid developments taking place in the construction industry, environmental problems, including the excessive use of natural resources and the increase in the amount of construction and demolition (C&D) waste, are becoming pressing issues. Approximately 2 billion tons of C&D waste, which amounted to 10% of the gross municipal waste, was generated in China in 2013 [1]. Recycled aggregate concrete (RAC) is attracting significant attention all over the world, as it is a very promising solution for dealing with C&D waste and saving construction materials [2].

In cold regions, hydraulic structures, such as bridges, dams, and ports, are susceptible to freeze/thaw (FT) cycling, which can lower their durability and result in structural deterioration. To expand the range of applications of RAC and explore the feasibility of using it in cold areas, it is essential to determine the frost resistance of RAC. Salem and Burdette [3] reported that the resistance of RAC to FT cycling of RAC can be improved by adding an air-entraining agent and higher amounts of fly ash to it. Salem et al. [4], Zaharieva et al. [5], and de Oliveira and Vazquez [6] found that the degree of water saturation is the critical factor determining the frost resistance of RAC. Ajdukiewicz and Alina [7] reported that a high-performance concrete prepared using RCA obtained from a high-performance parent concrete exhibited frost durability similar to or better than that of conventional concrete. Gokce et al. [8] found that the frost resistance of RAC produced using RCA

Abbreviations: ARAC, air-entrained recycled aggregate concrete; RCA, recycled coarse aggregate; C&D, construction and demolition; RAC, recycled aggregate concrete; FT, freezing and thawing; RDME, relative dynamic modulus of elasticity; URDME, ultrasonic RDME; WRA, water-reducing agent; WSSD, water-saturated surface dry density; ITZ, interfacial transition zone.

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derived from an air-entrained concrete was similar to that of conventional concrete, while RAC containing RCA derived from non-air-entrained concrete exhibited poor frost resistance. Kawamura and Torii [9] reported that the FT resistance of RAC can be improved by reducing the amount of adhering mortar in the RCA used. Abbas et al. [10] reported that the equivalent mortar volume method can help increase the frost resistance of RAC to the extent that it complies with the requirements of ASTM C666-97 [11].

However, there are few systematic studies on the effects of the parent concrete used on the frost resistance of RAC [8]. The mesostructure of RAC is far more complex than that of conventional concrete, owing to the presence of the adhering mortar on the surfaces of the RCA particles [12,13]. Several approaches have been proposed for enhancing the mesostructure of RAC, including handling the RCA directly [9,14–16] and modifying the mixing process used [13,17–18], while little research has been performed on the effects of the mixing method used on the FT resistance of RAC [19]. In addition, currently, macroscopic indices such as the mass loss and the relative dynamic modulus of elasticity (RDME) are used to assess the frost resistance of RAC [3–6,9], and analyses of its mesostructure after FT cycling are relatively rare [8].

The aim of this article is to study the effects of parent concrete and mixing method on the frost resistance of air-entrained recycled aggregate concrete (ARAC) on the macroscale and reveal the failure mechanism of ARAC during freezing and thawing cycles based on mesostructural analyses. First, a systematical study was carried out to elucidate the effects of the parent concrete used on the frost resistance of ARAC on the basis of four macroscale indices, namely, the mass loss, the RDME, the ultrasonic RDME (URDME), and the strength loss. Three mixing approaches were explored in this study. Finally, a possible mechanism for the failure of ARAC after FT cycling is proposed on the basis of the results of mesostructural analyses.

2. Experimental

2.1. Materials

2.1.1. Parent concrete

Iron oxide red was added to air-entrained type concrete and partial non-air-entrained type concrete as colorant, in order to be able to distinguish between the new mortar and the residual mortar during the subsequent mesostructural analyses. The added iron oxide red had little effect on the parent mortar, which exhibited stabilities high enough to satisfy the test requirements (Table 1). Four parent concretes were designed for this study; their compositions are listed in Table 2. The properties of the freshly prepared and hardened parent concretes are listed in Table 3.

2.1.2. Concrete mixes ingredients

The parent concrete samples were cured under standard conditions (20 ± 2 °C and 95% relative humidity) for 90 days before being crushed. They were subjected to a primary crushing process, using a jaw crusher. RCA samples with particles with diameters of 4.75–26.5 mm were selected after screening. The physical properties of the coarse aggregates are shown in Table 4 [20]. With an increase in the strength of the parent concrete used, the crushing index and water absorption rate of the RCA decreased, in agreement with the results of Padmini et al. [22]. However, the values of these parameters were greater than those of natural aggregate. In addition, the water-saturated surface dry density (WSSD) and residual mortar content of the RCA increased with the increase in the strength of the parent concrete, consistent with the study of Etxeberria et al. [23]. The higher crushing index in the case of the AC type were probably owing to the decreases in strength caused by the entrainment of air in the parent concrete. The particle size distribution for all the aggregates met the grading requirements, according to standard GB/T 25177-2010 [24]. The cementitious material used in this study was ordinary

Table 3
Properties of freshly prepared and hardened parent concretes.

Type	Slump (mm)	Air content (%)	Compressive strength on 28th day (MPa)
L	110	1.2	34.9
M	100	1.1	47.2
MR	90	1.2	45.9
H	120	1.1	57.3
AR	130	5.5	36.7

Table 4
Physical properties of coarse aggregates.

ID	Source	WSSD (kg/m^3)	Water absorption (%)	Crushing index (%)	RMC[a] (%)
CG	Natural gravel	2772	0.6	2.6	–
LC	L	2476	6.4	15.1	35.4
MC	M	2515	5.6	11.7	37.2
NC	MR	2480	6.8	11.8	42.5
HC	H	2539	4.6	7.8	42.1
AC	AR	2415	5.9	12.6	41.7

[a] Residual mortar content, determined by a previously reported method [21].

Table 1
Effects of colorant on properties of parent mortar.

Type		Composition of parent mortar					Air content (%)	Compressive strength on 28th day (MPa)
		Cement (kg)	Water (kg)	Sand (kg)	AE[a] (‰)	C[b] (%)		
Non-air-entrained	Noncolored	1	0.45	1.314	–	–	1.5	31.1
	Colored	1	0.45	1.314	–	5	1.7	30.0
Air-entrained	Noncolored	1	0.45	1.314	0.05	–	7.9	23.5
	Colored	1	0.45	1.314	0.05	5	8.4	24.0

[a] Air entraining agent (alpha olefin sulfonate, permillage for cement).
[b] Colorant (percentage of cement weight, added together with cement).

Table 2
Approaches used to mix the parent concrete (1 m^3).

Type		ID	w/c	Cement (kg)	Water (kg)	Sand (kg)	Natural coarse aggregate (kg)	WRA[a] (%)	C (%)	AE (‰)
Non-air-entrained	Low strength	L	0.60	342	205	685	1118			
	Moderate strength	M	0.45	456	205	599	1112			
	Moderate strength, colored	MR	0.45	456	205	599	1112		5	
	High strength	H	0.30	520	156	629	1169	7.8		
Air-entrained	Moderate strength, colored	AR	0.45	456	205	599	1112		5	0.05

[a] Water-reducing agent (naphthalene sulfonate, percentage of cement weight).