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Understanding restraint effect of coarse aggregate on the drying shrinkage of self-compacting concrete

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HIGHLIGHTS

- An aggregate skeleton dispersion model of SCC was proposed and the restraint mechanism of aggregate was analyzed.
- The relation between mortar coating thickness and the drying shrinkage of was established.
- The restraint mechanism of aggregate was clarified based on the aggregate skeleton dispersion model and theoretical analysis.
- Coarser aggregate provides better restraint on the volume deformation of mortar.

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ABSTRACT

Coarse aggregate serves as a restraint on the shrinkage of cement mortar, while the previous investigations mainly focused on normal vibrated concrete. In this study, effects of coarse aggregate volume and gradation on the drying shrinkage of self-compacting concretes (SCCs) were studied, and the mortar coating thickness (H_{MCT}) was defined and calculated based on an aggregate skeleton dispersion model. The results indicate that the shrinkage of SCCs was mainly influenced by the H_{MCT} and the restraint of coarse aggregate. With the decrease of coarse aggregate volume, the shrinkage of SCCs increased remarkably, which is due to the increment of H_{MCT}. In another aspect, when coarse aggregate volume kept constant, the shrinkage of SCCs decreased with the increase of H_{MCT}, which can be attributed to the better restraint effect of coarser aggregate. Further, the maximum tensile stress induced by the aggregate restraint was calculated based on the elasticity theory. A larger size of aggregate induced a higher aggregate restraint coefficient and theoretical elastic stresses on the mortar.

1. Introduction

Generally, the shrinkage of cementitious materials paste, including chemical shrinkage, autogenous shrinkage, drying shrinkage et al., are considered as the main reason for the volume deformation of concrete. Among them, drying shrinkage is the major cause inducing cracking of concrete, consequently resulting in a rapid deterioration of structures [1]. It is thought that the shrinkage of paste is the main reason which may lead to cracking of concrete, and aggregate restrains the shrinkage of cement paste and consequently reduces the whole shrinkage of concrete [2].

Recently, more and more attention has been paid to study the influence of aggregate on shrinkage of concrete. Hansen et al. [3–8] reported that the aggregates play an important role in restraining the shrinkage of the cement matrix, which could reduce the shrinkage of concrete compared to plain hardened cement paste. Fujiwara and Goto [9] also indicated that the role of aggregate is to confine the volumetric change of concrete. Tangtermsirikul [10] proposed a model for simulating the effects of the stiffness of aggregate on shrinkage of concrete. The research indicated that the shrinkage of concrete is affected by the content, gradation and strain of aggregate. Aggregate serves as a restraint on the shrinkage of cement paste [11–13], previous investigations mainly focused on the influence of aggregate on the drying shrinkage of normal vibrated concrete, in which the aggregate content is normally in the range of 70%–80% of the total concrete volume. SCCs contains a larger volume of cementitious materials and smaller amount of aggregate (<60%), resulting in a larger drying shrinkage and higher potential cracking risk [14]. Therefore, clarifying the effects of aggregate on the drying shrinkage of SCCs is more important.

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The objective of this study is to investigate the volume and gradation of coarse aggregate on the drying shrinkage of SCCs. An aggregate skeleton dispersion model was proposed to determine the mortar coating thickness (H_{MCT}), and the relationship between H_{MCT} and drying shrinkage of SCCs was analyzed. Further, based on the aggregate skeleton dispersion model and theory of elasticity, the maximum tensile stress induced by the aggregate restraint was calculated, and the related mechanisms were discussed by the combination of the drying shrinkage of the matrix and the restraint of aggregate.

2. Experimental

2.1. Materials

Type II(CEM II/42.5R) Portland cement, granulated blast furnace slag (GBFS) and low calcium fly ash (Class F fly ash according to ASTM C 618) were used in this study. The chemical compositions of Portland cement, GBFS and fly ash are presented in Table1.

Crushed granite with a maximum size of 20 mm was used as coarse aggregate (with an apparent density of 2640 kg/m^3), and manufactured sand was used as fine aggregates (with a fineness modulus of 2.8 and apparent density of 2620 kg/m^3). A polycarboxylate superplasticizer (SP, with a specific gravity of 1.08 kg/m^3 and solid content of 25%) produced by Sika Chemical Company was used.

2.2. Mixture proportions

For ten concrete mixtures listed in Table 2, the binders were consisted of 69.6% Portland cement, 13% fly ash, and 17.4% GBFS, the binder/fine aggregate mass ratio was 0.55, water/binder mass ratio (W/B) was 0.35, and SP to binder mass ratio was 0.9%. In order to investigate effects of coarse aggregate volume on the drying shrinkage of SCCs, five mixtures with the coarse aggregate volume of 34%, 33%, 32%, 31%, 30% respectively were designed, in which original 5–20 mm original coarse aggregate was used. By changing the relative mass ratio of 5–10 mm, 10–16 mm and 16–20 mm coarse aggregates (10%:30%:60%, 20%:30%:50%, 30%:30%:40%, 40%:30%:30%, 50%:30%:20%), another five mixed coarse aggregates were designed to investigate effects of coarse aggregate gradation on the drying shrinkage of SCCs with 30% coarse aggregate volume. The particle size distributions of coarse aggregates used are given in Fig. 1.

2.3. Testing methods

2.3.1. Workability of SCCs

The slump flow, T500 time, V-funnel flowing time and U-box filling height were determined according to European guidelines for self-compacting concrete [15] and publication [16] to evaluate the workability of SCCs (in terms of flowability, passing ability and segregation resistance).

2.3.2. Drying shrinkage of SCCs

Fresh concretes were casted into 100 × 100 × 400 mm moulds, then covered by a polyethylene film and cured at 23 ± 2 °C for 24 h. After the demolding, the initial length of prism was measured by using a contact-type LVDT immediately, then specimens were moved to an environmental chamber (50% RH, 23 ± 2 °C), length change of prisms was followed at desired ages.

3. Results

3.1. Workability of SCCs

Table 3 shows that the slump flow of SCCs increased with the decrease of coarse aggregate volume. For instance, the slump flow of SCC_{34} (with a coarse aggregate volume of 34%) is 580 mm, and 620 mm for SCC_{30}, only SCC_{34} presented a slump flow smaller than 600 mm (the minimum slump flow of target SCC). When the volume of coarse aggregates reduced, both T500 time and V-funnel flowing time decreased, and U-box filling height increased, indicating an improvement of workability of SCCs. To meet the requirements of workability, the coarse aggregate volume should be lower than 34%.

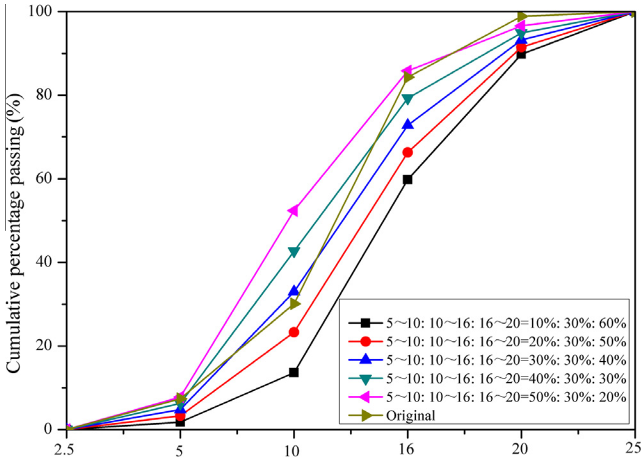

Fig. 1. Particle size distributions of coarse aggregates.

Table 1
Chemical compositions of Portland cement, GBFS, and fly ash used.

Material	Density (g/cm^3)	Chemical compositions (%)								
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	LOI
Portland cement	3.14	21.86	4.45	2.35	63.51	1.67	0.55	0.26	2.91	1.89
GBFS	2.80	35.22	12.15	0.25	37.08	11.25	0.49	0.25	1.19	−0.36
Fly ash	2.35	49.20	24.82	9.70	7.23	3.50	1.20	1.00	1.03	1.92

Table 2
Mixture proportions of SCCs in the present study.

No.	Coarse aggregate					Portland cement (kg/m^3)	Fly ash (kg/m^3)	GBFS (kg/m^3)	Fine aggregate (kg/m^3)	Water (kg/m^3)
	Mass (kg/m^3)	Volume ratio (%)	Relative mass ratio (%)							
			5–10 mm	10–16 mm	16–20 mm					
SCC_{34}	880	34	15	55	30	312	58	78	817	157
SCC_{33}	860	33				316	59	79	829	159
SCC_{32}	840	32				320	60	80	840	161
SCC_{31}	820	31				324	61	81	851	163
SCC_{30}	800	30				329	62	82	864	166
$SCC_{10\text{-}30\text{-}60}$	800	30	10	30	60	329	62	82	864	166
$SCC_{20\text{-}30\text{-}50}$			20	30	50					
$SCC_{30\text{-}30\text{-}40}$			30	30	40					
$SCC_{40\text{-}30\text{-}30}$			40	30	30					
$SCC_{50\text{-}30\text{-}20}$			50	30	20					