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- Technical Report -

MIXTURE DESIGN OF STEEL FIBER-REINFORCED CONCRETE WITH AN ORDINARY AGGREGATE GRADATION

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ABSTRACT

This study investigated the mixture design of steel fiber-reinforced concrete considering an ordinary aggregate gradation with a maximum aggregate size of 20mm. The coarse aggregate content was varied to obtain the optimum packing density to include 1.0 Vol.% fibers; the effects on workability and the stability of volume and stiffness in the hardened state were examined. It showed that reducing the coarse aggregate content to reach a relative packing density of about 0.99 was crucial for obtaining stable and highly workable slumped concrete. The effects of lowering coarse aggregate content on drying-induced shrinkage and elastic modulus were moderate within the studied mixtures.

Keywords: steel fiber, coarse aggregate content, packing density, workability, slump

1. INTRODUCTION

Extended and reliable structural use of steel fiber-reinforced concrete (SFRC) requires an essential dosage of fibers in concrete with a closely uniform dispersion to achieve the specified mechanical properties and performance consistency. However, adding a high volume of rigid long steel fibers may significantly impair fresh concrete's workability. To address this issue, the use of self-compacting concrete has been extensively studied to take advantage of its high flowability to disperse the fibers and achieve super-workable SFRC. In the recommended mixture designs, decreasing the maximum aggregate size is commonly applied since the movement of fibers is restricted in the matrix with large aggregates [1, 2]. For instance, a nominal maximum aggregate size of 9.5-10mm was adopted in [3, 4]. In practice, such a specific aggregate gradation does not conform to those stipulated in JIS A 5308 [5], hindering its applicability.

This work studied the mixture design of SFRC using the aggregates with an ordinary gradation, aiming at general use. As Rossi and Harrouche suggested, the most workable concrete is the most compactable, and its granular skeleton is optimal, which also applies to SFRC [6]. In addition, the study on PVA fiber-reinforced concrete mixtures conducted by Nakamichi and Ueda [7] found that the mixture showing the greatest workability had the maximum packing density. The decreased porosity of the granular skeleton (fibers and aggregates) resulted in a thicker paste layer that ensures workability. Therefore, this work adopted a similar design concept of maximizing the packing density for the fiber-aggregate matrix by adjusting the coarse aggregate content.

The effect of the steel fibers with different aspect ratios on the packing density was experimentally studied to find a suitable coarse aggregate content to include fibers. Then, trial batch studies were carried out to investigate the effects on workability and the stability of mechanical performance.

2. OPTIMIZATION OF PACKING DENSITY

2.1 Aggregates and Fibers

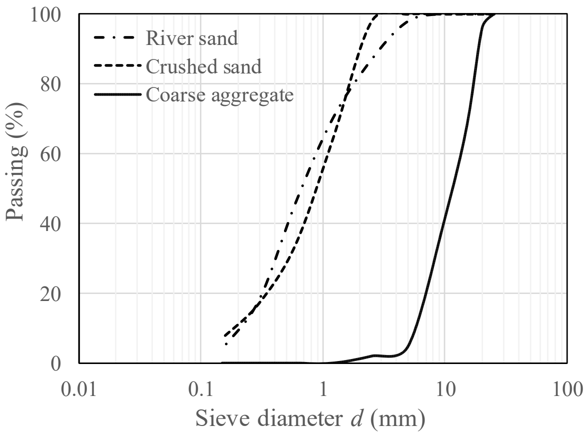

Fig.1 Particle size distribution of fine and coarse aggregates

A mix of river and crushed sand (0.15-5mm) with fineness moduli of 2.75 and 2.81, respectively, were used, and their volume ratio was kept as 3:7. The sand had oven-dry-based densities of 2.54 and 2.63g/cm^{3,} respectively, and absorption rates of 1.34 and 1.21%, respectively. As for gravels, crushed sandstone with a nominal maximum aggregate size of 20mm, which had an oven-dry density of 2.64g/cm^3 and an absorption rate

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Table 1 Characteristics of the fibers

Type	Diameter (mm)	Length (mm)	Aspect ratio α	Minimum tensile strength (MPa)	Elastic modulus (GPa)	Remarks
α45	0.62	30	45	1080	210	loose
α65*	0.55	35	65	1143		glued in bundles
α80*	0.38	30	80	2610		glued in bundles

* The bundles were separated into individual fibers before the tests of packing density.

of 0.58%, was used. The particle size distribution of fine and coarse aggregate is shown in Fig. 1.

The steel fibers of different aspect ratios, which are deformed with hooked ends, were applied. Table 1 presents the characteristics of the fibers.

2.2 Experimental set-up

The tests on packing density were performed following JIS A 1104 [8], in which the sand-to-aggregate (s/a) ratio varied from 35 to 75 Vol.% to find the optimum for each type of steel fiber studied. For preparation, the fine and coarse aggregates were oven-dried at 105°C for 24 hours, and the quantities were measured with a 10% surplus. They were carefully mixed using a shovel for at least 60s. The fiber content applied was 1.5 Vol.% of aggregates, corresponding to 1.0 Vol.% of concrete assumed to have a paste content of 32 Vol.%. The fibers were added by hand while remixing with the aggregates until the fibers appeared uniformly distributed. The blend was then reduced to test sample size in accordance with JIS A 1158 [9].

Since the compaction method greatly impacts the packing density results, this study employed vibrations in addition to the rodding procedure specified in JIS A 1104 [8]. First, the test container of 10L was filled in three layers, and each layer was rodded with 30 strokes. The masses of the container plus the test sample and the container alone were measured to determine the packing density PD (see Eq.1). Next, two minutes of vibration were adopted with an even compression force applied on the test sample. The insufficient amount was supplemented afterward, and a new PD was decided. This compaction method is similar to that in [10].

$$PD = M/Vd \qquad (1)$$

where,

M : the sample mass (g)

V : the volume of the container (ml)

d : the oven-dry density of the test sample calculated with each fraction's density and volume content (g/cm^3)

2.3 Experimental Results of Packing Density

Fig. 2 shows the effect of the compaction method on the packing density. Note that each data is an average of two measurements. The further vibrations apparently increased the packing densities by 3.0-5.5% for both plain and fiber-added mixes. On the other hand, the s/a ratio to achieve the maximum packing density appears independent of the compaction method. Hence, the study hereafter used the relative packing densities by dividing with each group's maximum to disregard the effect of the compaction method.

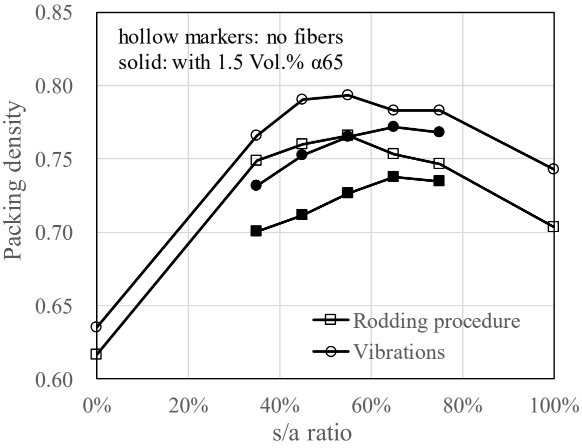


Fig.2 Effect of compaction on packing density

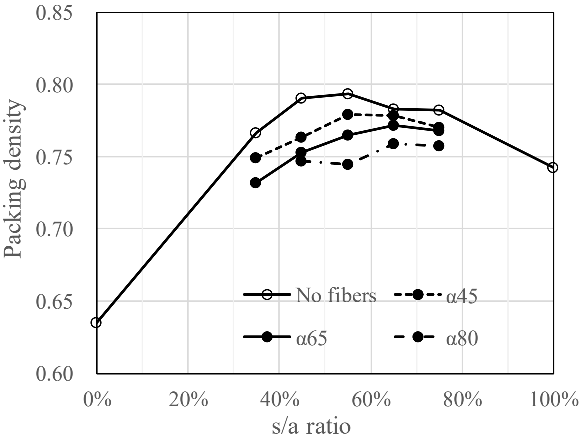


Fig.3 Effect of fiber aspect ratio on packing density (with vibrations)

Fig. 3 compares the packing densities between different fiber types. Adding fibers with a higher aspect ratio resulted in a more pronounced decrease in the packing density, suggesting an increased demand for paste to fill the voids. Moreover, the maximum shifts towards a higher s/a ratio. In the case of α80, the s/a ratio of about 65-75 Vol.% led to its maximum packing density, while for α45, it was 55 Vol.%, close to that without fibers. To compensate for the effect of fibers, the aggregate composition needs an adjustment that reduces the coarse aggregate content. The same trend was reported in [10] using round sand (0.125-4mm) and smaller crushed coarse aggregates (4-16mm).

2.4 Assessment of Packing Density

In the practice of concrete mixture design, the input of unit water content and coarse aggregate content is commonly required. Both variables affect the sand content and, consequently, the s/a ratio considering a given water-to-cement/binder (W/B) ratio dependent on the specified strength. Hence, to include fibers, a series of combinations needs to be assessed to achieve the optimized packing density. This study examined a range of unit water content of 160-185kg/m^3 and coarse aggregate content of 0.22-0.32m^3/m^3 for the studied fibers by interpolating the test results of packing density. It corresponds to a range of s/a ratio of 46.5-66.0% for a W/B ratio of 0.39. Further reducing the coarse aggregate content would rather impair the packing density. It is worth mentioning that the unit water content of 185kg/m^3 is deemed the upper limit specified in the AIJ guideline on concrete mixture design [11]. The coarse aggregate content of 0.31m^3/m^3 occupying a bulk volume of 0.5m^3/m^3 corresponds to the lower bound suggested by the AIJ's guideline on high fluidity concrete [12].

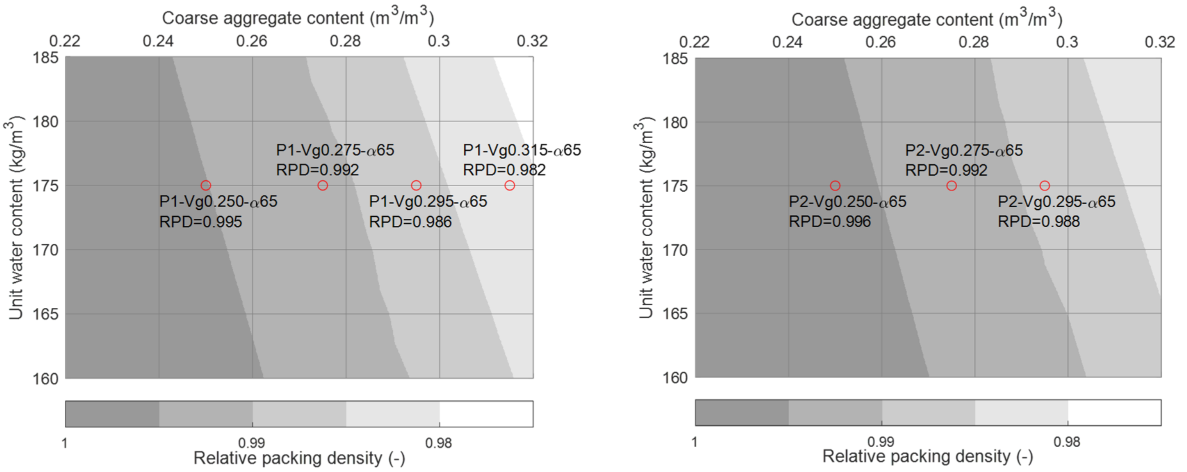
Fig. 4 shows gray-level contours of relative packing density for the cases with a W/B ratio of 0.39 and various types of fibers. A case of a W/B ratio of 0.45 with the α65 fibers was also included for comparison. It can be seen that the packing density is primarily dominated by coarse aggregate content. The coarse aggregate content must be reduced to obtain the maximum packing density for the studied fibers. For example, in the case of α80, the permissible range was 0.225-0.24m^3/m^3.

Trial batches were then carried out to investigate the effect of reducing coarse aggregate content on the fiber-reinforced concrete's workability. The volume and stiffness stability in their hardened state were also examined, as there were concerns that a comparatively small coarse aggregate content would result in significant drying-induced shrinkage and a decrease in elastic modulus [12].

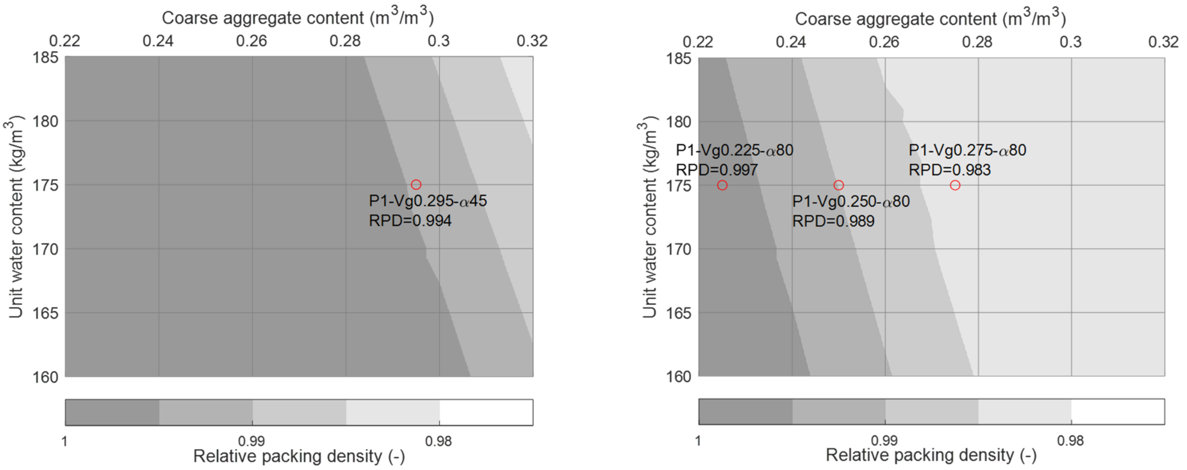
3. TRIAL BATCH STUDIES

3.1 Paste Composition and Concrete Mixture Proportioning

Binary blended type C equivalent Portland blast-furnace slag cement containing approximately 30% high early strength cement and 70% granulated blast-furnace slag was used as the binder. Limestone powder of about 7.0% in the mass ratio of binder was added as a filler to increase the resistance to concrete segregation. The water-reducing agent (WR) was a polycarboxylic-acid-typed WR. Air-entraining or defoaming agents were also used to maintain the concrete air content at 4.5±1.5%.



(a) W/B 0.39 – 1%α65 (b) W/B 0.45 – 1%α65



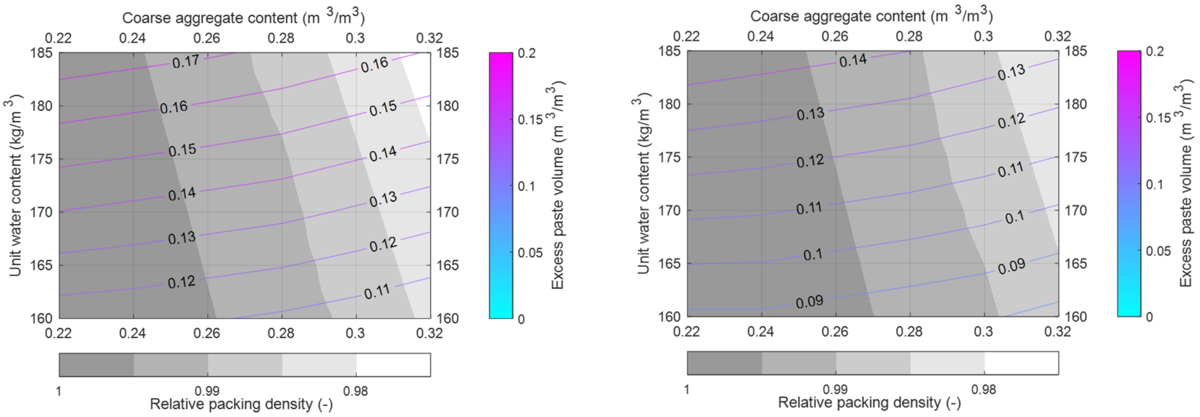
(c) W/B 0.39 – 1%α45 (d) W/B 0.39 – 1%α80

Fig.4 Contours of packing densities for various unit water contents and coarse aggregate contents

Table 2 Mixture proportioning investigated (fiber content: 1.0 Vol.%)

Mixture series	W/B ratio	Water (kg/m^3)	Binder (kg/m^3)	WR agent (%. b)	Coarse aggregate content (m^3/m^3)	s/a volume ratio	PD*	RPD*	Excess paste volume (m^3/m^3)	Fiber aspect ratio
Ref. 1	0.39	175	449	0.55	0.295	52.2%	0.793	0.999	0.176	-
Ref. 2	0.45	175	389	0.62	0.295	53.8%	0.793	1.000	0.149	-
P1-Vg0.315-α65	0.39	175	449	0.55	0.315	49.0%	0.758	0.982	0.137	65
P1-Vg0.295-α65	0.39	175	449	0.55	0.295	52.2%	0.761	0.986	0.141	65
P1-Vg0.275-α65	0.39	175	449	0.55	0.275	55.5%	0.765	0.992	0.145	65
P1-Vg0.250-α65	0.39	175	449	0.55	0.250	59.5%	0.768	0.995	0.148	65
P2-Vg0.295-α65	0.45	175	389	0.62	0.295	53.8%	0.763	0.988	0.115	65
P2-Vg0.275-α65	0.45	175	389	0.65	0.275	57.0%	0.766	0.992	0.118	65
P2-Vg0.250-α65	0.45	175	389	0.68	0.250	60.9%	0.769	0.996	0.121	65
P1-Vg0.295-α45	0.39	175	449	0.55	0.295	52.2%	0.775	0.994	0.155	45
P1-Vg0.275-α80	0.39	175	449	0.58	0.275	55.5%	0.746	0.983	0.124	80
P1-Vg0.250-α80	0.39	175	449	0.58	0.250	59.5%	0.751	0.989	0.130	80
P1-Vg0.225-α80	0.39	175	449	0.60	0.225	63.6%	0.757	0.997	0.136	80

* The packing densities (PD) are the interpolated values of the test results performed with vibrations, and the relative ones (PRD) are those against each group's maximum.



(a) W/B 0.39 – 1%α65 (b) W/B 0.45 – 1%α65

Fig.5 Contours of excess paste volume for various unit water contents and coarse aggregate contents

Table 2 gives the concrete mixture proportions investigated. The tested cases are named by paste type decided by the W/B ratio, coarse aggregate content, and fiber type. They are also depicted in Fig. 4 to show their packing densities. The reference mixtures without fibers were designed to approximate their maximum packing densities, and they both yielded a slump flow larger than 50cm without any sign of segregation. According to [4] and [10], to obtain similar flowability after adding fibers, the mixture needs to secure at least the same volume of excess paste V_e (see Eq.2) for enveloping aggregates and fibers. This, however, is unapproachable in the present study, with the upper limit of unit water content of 185kg/m^3. Fig. 5 shows the contour lines of excess paste volume for the cases with the α65 fibers and a W/B ratio of 0.39 and 0.45, respectively. Both cases cannot achieve the required excess paste volume (see Ref. 1 and 2 in Table 2). Watanabe et al. [13] reported a slump loss of about 8cm after adding 1.0 Vol.% α65 fibers. Accordingly, in this work, the acceptance requirement of the slump was set as 18.0±2.5cm, aiming at an easy-handling slump-type concrete.

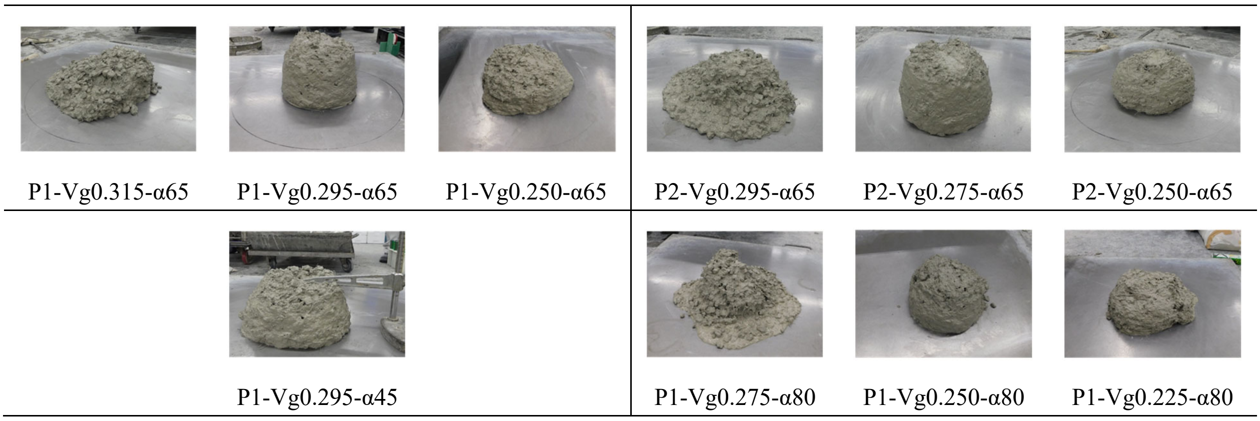
$$V_e = V_{paste} - \left(\frac{V_{solid}}{PD} - V_{solid}\right) \quad (2)$$

where,

V_{paste} : volume of paste (m^3/m^3)
V_{solid} : volume of aggregates and fibers (m^3/m^3)
PD : packing density calculated (-)

The concrete was mixed using a double-shaft forced mixer at a room temperature of approximately 20°C. The mixing was performed as follows: binder, limestone powder, and sand were dry mixed for 30 seconds, and then water pre-mixed with chemical admixtures was added and mixed for one minute. Next, the coarse aggregates were added and mixed for two minutes; the fibers were introduced later in this step. After that, the concrete was mixed for two or three minutes until the fibers were well dispersed.

The standard slump tests per JIS A1101 [14] were performed as soon as the fresh concrete was discharged. The cylindrical specimens 200mm high and 100mm in diameter were fabricated for compression tests, along with the prismatic specimens (400×100×100mm^3) for measuring drying-caused free shrinkage using contact-typed strain gauges following JIS A1129-2 [15]. As for


P1-Vg0.315-α65 P1-Vg0.295-α65 P1-Vg0.250-α65 P2-Vg0.295-α65 P2-Vg0.275-α65 P2-Vg0.250-α65

P1-Vg0.295-α45 P1-Vg0.275-α80 P1-Vg0.250-α80 P1-Vg0.225-α80

Fig.6 Comparison of the slumped shape between mixtures with different coarse aggregate contents

curing, two different schemes were applied to the specimens for compression tests, specifically the standard curing in water at 20°C and a steam curing with a peak temperature of 45°C. The temperature during the steam curing was initially kept at 20°C for the first two hours and increased to 45°C by 15°C/h. The peak temperature was maintained for three hours, and the specimens were then cooled to the ambient temperature. Those specimens were sealed and stored in a room at 20°C until the test age.

3.2 Test Results – Workability Characteristics

Fig. 6 compares the shape of the slumped concrete between different mixtures with various coarse aggregate contents. Those cases with a relatively high volume of coarse aggregates showed shear slump with the top portion sliding sideways (see P1-Vg0.315-α65, P2-Vg0.295-α65, and P1-Vg0.275-α80). Although their slump values met the requirement, the resulting compatibility issue between large aggregates and fibers may cause segregation and poor dispersion of fibers. With the paste composition in this study, lowering the coarse aggregate content to get a relative packing density of 0.985-0.99 is essential for obtaining the regular frustum shape.

Moreover, improved slump performance was observed in those cases with further reductions in the coarse aggregate content (see Fig. 6), which can be ascribed to the increase in excess paste volume. The measured slump values are plotted against the calculated excess paste volume in Fig. 7. Since the WR dosage-dependent paste's rheological properties also impact concrete workability [3], the calculations of the excess paste volume were corrected in proportion to their WR dosages. For simplicity, a dosage of 0.55% in the mass ratio of binder was set as the reference. Future studies on the paste's rheology regarding yield stress and viscosity will be carried out to establish a clear relationship. Nevertheless, Fig. 7 shows a good correlation between the excess paste volume and the slump value.

In general, the tests on workability suggest that reducing the coarse aggregate content to achieve a relative packing density larger than 0.99 helps to alleviate the incompatible problems between large aggregates and fibers and provides an essential volume of paste, which leads to stable and greatly workable slumped concrete.

3.3 Test Results – Volume and Stiffness Stability

Fig. 8 shows a comparison of drying-induced free shrinkage between the plain mixture without fibers and the fiber-reinforced ones with different coarse aggregates, which all had a W/B ratio of 0.39. It appears that the addition of 1.0 Vol.% steel fibers had little influence on the development of drying shrinkage. After 26 weeks of drying, lowering the coarse aggregate content from 0.295 to 0.25m^3/m^3 caused a shrinkage increase of only 6.0%.

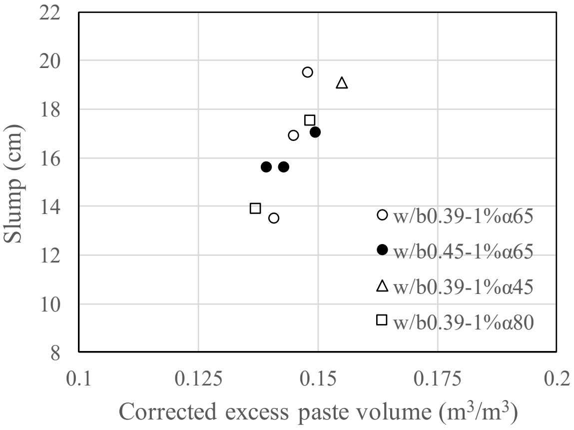


Fig.7 Excess paste volume versus slump value

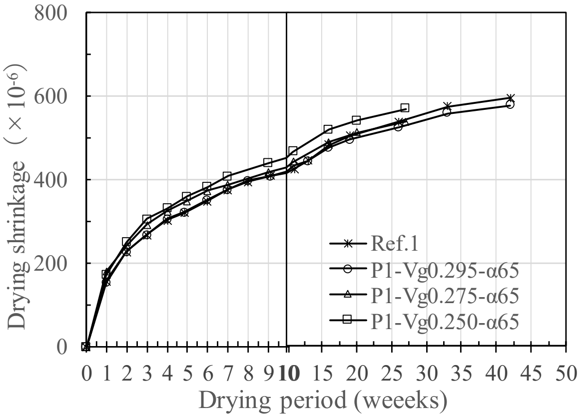
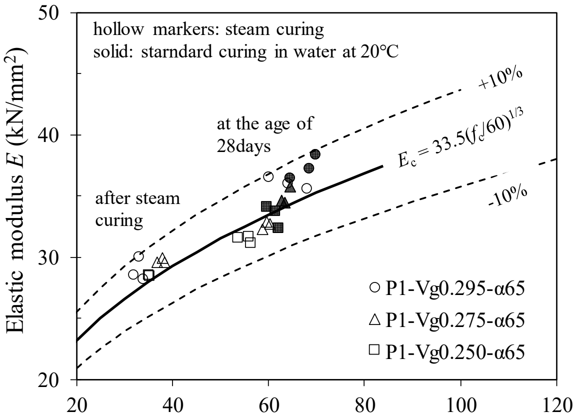
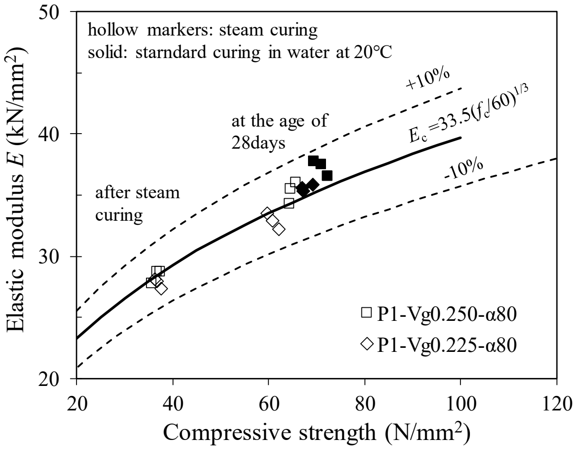


Fig.8 Drying shrinkage for the mixtures of P1-α65 with different coarse aggregate contents

Fig 9 compares the data of elastic modulus obtained in the compression tests. The elastic modulus apparently dropped as the coarse aggregate content decreased. The values, however, still lay within the 10% range of the predictions with the New RC equation. It confirms that, within the range of the concrete mixtures studied, lowering the coarse aggregate content to 0.225m^3/m^3 would not cause detrimental effects on their volume and stiffness stability.



(a) P1-α65



(b) P1-α80

Fig.9 Elastic modulus versus compressive strength

4. CONCLUSIONS

The experimental study presented allows drawing the main concluding remarks listed in the following:

(1) Reducing the coarse aggregate content to approach the maximum packing density for a fiber-aggregate matrix is crucial for achieving stable slumped concrete. A relative packing density of 0.99 against the maximum is preferred. This study suggested a maximum coarse aggregate content of 0.28m^3/m^3 for the α65 fibers and 0.24m^3/m^3 for the α80 fibers.

(2) The slump performance of concrete depends on the volume of excess paste and the paste's rheological nature. Reducing the coarse aggregate content with improved packing density can provide more excess paste and enhance the concrete's workability. More studies on the effects of unit water content and WR dosage on the paste nature are required to establish a generalized mixture design model.

(3) The effects of reducing coarse aggregate content on the concrete's volume and stiffness stability were considered tolerable within the investigated concrete mixtures.

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