Long-term shrinkage behaviour of steel-concrete composite slabs with recycled coarse aggregate

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Abstract. Non-uniform shrinkage profile through the slab thickness is observed in composite slabs with natural concrete due to the inability of the slabs to dry from their underside, including an additional deflection for composite slabs under the serviceability state. The porosity and shrinkage deformation of recycled aggregate concrete (RAC) are remarkably increased by the residual mortar adhered to the surface of recycled coarse aggregate (RCA), which will complicate the ability to predict the serviceability of composite slabs with RCA. In this study, two full-scale RAC specimens with depths of 120 mm and 180 mm were prepared and tested for 140 days, with the mid-span and quartiles-span deflections were measured; two small-scale solid concrete samples were poured and measured monitoring the development of non-uniform shrinkage. Results obtained indicated that the non-uniform shrinkage through the slabs depths was approximately linear-distributed, the gradient of which increased with curing time, however, decreased remarkably with the increasing slabs depths. The long-term deflections of two full-scale specimens were remarkably influenced by the non-uniform shrinkage. Based on EC2, a modification of notation size of member (h) was used to predict the shrinkage strain on the top surface of the slabs with one way to diffuse moisture, and the predicted data well match the experimental results.

1. Introduction
The recycled coarse aggregate (RCA) obtained by crushing waste concrete not only reduces the economic loss and environmental impact caused by the disposal of waste concrete, but also reduce of need of natural sand and stones [1-2]. Therefore, RCA concrete has been widely concerned by scientific researchers and engineering. Compared with natural coarse aggregate (NCA) concrete, RCA concrete has lower compressive strength and elastic modulus, larger shrinkage and creep and therefore the structural application of RCA concrete is still mainly limited to non-structural components [3-5]. In fact, the experimental research results show that RCA concrete can be applied to concrete structural members [6-13]. Moreover, many countries have promulgated the design specifications and technical regulations of recycled concrete structures, e.g. [14], by limiting the properties of RCA and the maximum content. Driven by experimental research and normative regulations, the use of recycled concrete in concrete structural components is increasing.

In recent years, some scholars have considered the introduction of RCA concrete in steel-concrete composite slabs, taking advantage of the high bearing capacity and rigidity of composite panels to make up for the shortcomings of lower mechanical properties of RCA concrete. The obtained static performance (bending resistance and shear bonding performance) of the RCA concrete composite slab was tested. The research results show that the composite slabs with recycled concrete can meet the
requirements of corresponding codes. However, regarding the long-term performance of recycled concrete composite slabs, especially the impact of the shrinkage properties of recycled concrete on its serviceability limit state behaviour, no relevant experimental studies have been seen at home and abroad. For NCA concrete composite panels, due to the presence of profiled steel sheeting, the humidity inside the concrete can only be transmitted in one direction, and as a result, the shrinkage in the composite slabs shows a non-uniform distribution trend, resulting in additional curvature, which affects the performance of the serviceability limit state behaviour of the composite slabs [15-16]. However, the effect of non-uniform shrinkage on the service behaviour of the composite slab is ignored by most specifications.

To study the effect of non-uniform shrinkage of RCA concrete on its performance under serviceability limit state, two full-scale test of steel-RCA concrete composite slabs were carried out in this paper. The mid-span and quartiles-span deflections of the specimens under the effects of shrinkage and the quarter-point were measured. Meanwhile, the experimental study of shrinkage distribution on two small-scale specimens with bottom surface sealed was conducted.

2. Test overview

The test is mainly divided into two aspects: the full-scale test of the steel-RCA concrete composite slab and the non-uniform shrinkage distribution on the small-scale specimens.

2.1. Aggregate properties

This test uses 42.5 ordinary Portland cement produced by Changchun Yatai Cement Plant, with an apparent density of 3.17 g/cm³; The fine aggregate (NFA) uses natural river sand (0-5 mm), and the fineness modulus is 2.58; the recycled coarse aggregate used in the test originated from the waste concrete of a building demolition in Harbin, and the design strength of the waste concrete is C30, The service life in a Class I environment is 19 years, and other relevant information is unknown. The RCA is crushed in two stages: clamp excavators are used for mechanical crushing at the construction site, and the obtained waste concrete block was transported to the laboratory to be crushed with an jaw crusher, and the aggregate particle size range was 5 to 25 mm (recycled coarse aggregate with a particle size exceeding 25 mm was crushed by the jaw crusher).

2.2. Properties of concrete and steel materials

The content of each component of the recycled concrete used in this paper is shown in Table 1. The water-cement ratio of the recycled concrete is 0.45. To ensure that the recycled concrete has good workability, the recycled coarse aggregate is immersed in water for 24 hours before the test, and after drying in the indoor environment for 1 hour. Recycled concrete used in all specimens had similar slump values (about 17 cm).

The curing conditions of the concrete test blocks are the same as those of the full-scale test specimens. They are all covered with a thin plastic film (wet curing) and exposed to the indoor environment after 7 days from casting. The compressive strength of concrete for 28 days is 36.3 MPa, and the elastic modulus of prism for 28 days is 26.3 GPa. The shrinkage of recycled concrete are measured using prism test blocks. The DEMEC point was pasted on the surface of the test piece to measure the long-term deformation of the test piece. The recycled concrete used in this test has a dry shrinkage strain of $591 \times 10^{-6}$ at 140 days.

| Content of each component (kg/m³) | Slump (cm) | Compressive strength (MPa) | Elasti Modulus (GPa) |
|----------------------------------|------------|---------------------------|---------------------|
| water cement sand RCA superplasticizer | 180 400 620 1102 4.0 | 17±2 | 36.3 | 26.3 |

The profiled steel sheeting samples were subjected to a tensile test, and the elastic modulus of the steel sheeting was 199.7 GPa, and the yielding and the ultimate strength were 440.3 MPa and 517.0 MPa, respectively.
2.3. Long-term shrinkage test
The arrangement of the test specimens in the full scale test is shown in Fig 1. The total span and width of the test specimens was 3300 mm and 510 mm, respectively. The depth of the test specimens was 120 mm and 180 mm, and the specimen were named as CS-120 and CS-180. The profiled steel sheeting was YX-65-170-510, with a thickness of 1.2 mm and a height of 65 mm. When the concrete was poured, temporary support was arranged at the bottom of the specimen to prevent local instability of the profiled steel sheeting during the pouring process, and the support was removed after the concrete was initially set. After the concrete was poured for 24 hours, the mould was demolished, and the four sides of the full-scale specimens were sealed with epoxy resin to ensure that the full-scale specimens can only transmit moisture in one direction. In the test, the mid-span and quartiles-span deflections were measured, and the end slip between the steel sheeting and the concrete was measured.

![Fig. 1 Arrangement of full-scale test device](image)

To study the trend of shrinkage through the thickness of steel-RCA concrete composite slab, two scale test pieces were cast at the same time as the full-scale test of the solid samples. The plane dimensions of the test specimens were 600 × 600 mm², and the thickness was the same as that of the corresponding full-scale specimens, which were 120 mm (referred to as ES-120) and 180 mm (referred to as ES-180), respectively. To eliminate the restraining effect of the steel sheeting on the concrete, the steel sheeting was not placed in the test specimens. Before the concrete was poured, three groups of strain gauges were embedded in the thickness direction to measure the shrinkage strain distribution inside concrete. Similar to the full-scale boundary, the mould was demolished 24 hours after the concrete was poured, and the four sides and bottom of the solid specimens were sealed with epoxy resin. After the test specimens were removed from the mould, they were placed vertically on three rolling supports to ensure that the test specimens can move freely. The top and bottom surfaces of the non-uniform shrinkage piece were measured for shrinkage strain using DEMEC strain gauges.

3. Discussions of test results
The deflection of the steel-RCA concrete composite slabs under long-term shrinkage is shown in Fig. 2. The two specimens showed similar deflection changes. Due to the use of surface-saturated dry aggregate in the recycled concrete, a large amount of additional mixing water was mixed into the recycled concrete, which resulted in a relatively high relative humidity at the initial moment inside the concrete. The concrete exhibited a swelling phenomenon, so both specimens produced a "negative displacement" at the initial moment. The mid-span deflection of specimen CS-120 under the 140-day shrinkage was 5.33 mm (approximately L / 560); for the specimen CS-180, the mid-span deflection of specimen CS-180 under the 140-day shrinkage was 3.22 mm (approximately L / 930). Combining the mid-span deflections of the two specimens, it can be found that the effect of the long-term shrinkage of the recycled concrete on the composite slab decreases as the slab thickness increases. At the same age, the mid-span deflection of specimen CS-180 was only 60.2% of specimen CS-120.
As shown in Fig. 3, under the condition of single-sided moisture transmission, the two scale specimens showed a significant non-uniform shrinkage distribution trend. Because the bottom surface of the ES-120 specimen was not completely sealed, the bottom surface of the specimen after 28 days caused abnormal strain changes, as shown in Fig. 3 (a). In order to simplify the analysis, the non-uniform shrinkage distribution in this paper was considered to be approximately a linear distribution, and the shrinkage gradient was calculated using the shrinkage values on the top surface of the specimen and 1/4 depth from the bottom of the specimen.

Under single-sided moisture transmission condition, the shrinkage value of the top surface of the concrete slab changes drastically because the humidity of the top surface of the concrete changed significantly. In contrast, the humidity change of the concrete bottom surface was relatively small, and therefore, the change in the bottom strain was small. As the curing age increased, the non-uniform shrinkage gradient also increased. For the 180mm thick specimen, its shrinkage gradient increased significantly from $0.61 \times 10^{-6} \text{ mm}^{-1}$ for 7 days to $3.23 \times 10^{-6} \text{ mm}^{-1}$ for 140 days. The same law can also be obtained in the test piece ES-120, and its change trend was more obvious: for the 120mm thick specimen, its 140-day shrinkage gradient ($5.19 \times 10^{-6} \text{ mm}^{-1}$) was about 7-day shrinkage gradient ($0.72 \times 10^{-6} \text{ mm}^{-1}$).

From the trend of the shrinkage along the thickness of the test specimen ES-180, it can be found that the shrinkage value of the bottom surface of the non-uniform shrinkage sample was only about 10% of the shrinkage value of the top surface. Therefore, after the "normalized" processing of the non-uniform shrinkage gradient of the test specimens ES-120 and ES-180 with time and the change in shrinkage measured by the prism shrinkage test specimen over time, the results are shown in Fig. 4. It can be seen that the three curves presented similar changes.
Fig. 4 Normalized law of non-uniform shrinkage gradient and shrinkage strain over time

For the shrinkage prims (100 × 100 × 400 mm³), the 140-day shrinkage was 532 × 10⁻⁶, and the shrinkage value predicted by the EC2 specification was 518 × 10⁻⁶, indicating that the EC2 specification can effectively predict the shrinkage strain. For the non-uniform shrinkage specimens ES-120 and ES-180, the 140-day shrinkage values of the upper surface were 597 × 10⁻⁶ and 503 × 10⁻⁶, respectively, however, the predicted shrinkage using the corresponding EC2 specifications were only 234 × 10⁻⁶ and 156 × 10⁻⁶, and the test results differed greatly from the test results. For the shrinkage of NCA concrete in reference [15] under single- and double-sided moisture transmission conditions for 239 days (the corresponding specimen information and test data are summarized in Table 2), it was recommended to use the EC2 specification to predict the shrinkage value of concrete under the condition of single-sided confinement based on the double-sided confinement specimens. The nominal size $h_0$ was still calculated according to the traditional $2A_c / U$, but the $U$ is calculated under the condition of double-sided opening, and the corresponding prediction result needs to be enlarged by 1.2 times. Using the modified prediction method, the shrinkage values on the top surface of the specimens were 539 × 10⁻⁶ and 456 × 10⁻⁶, respectively, which were within 10% of the test results.

Table 2 Test conditions and related data summary in [15]

| Specimen ID | $l\times b\times d$ (mm³) | $f_{cm}$ (MPa) | $T$ & RHb | Test conditions | $\varepsilon_{239c}$ (10⁻⁶) |
|-------------|--------------------------|----------------|-----------|----------------|-----------------|
| S-1         | 900×900×180              | 33.7           | 22.3°C   | Double-sided moisture transmission | 500             |
|             |                          |                | 61.8%    | Single-sided moisture transmission | 610             |

$^a f_{cm}$ is the cylinder compressive strength;
$^b T$ & RH are the average temperature and relative humidity during the test, respectively;
$^c \varepsilon_{239}$——239-day shrinkage value.

4. Conclusions
(1) The deflection of composite steel-recycled coarse aggregate concrete slabs was significantly influenced by the non-uniform shrinkage, and the influence magnitudes decreased with increasing slab depths. For the slab specimen with thickness of 120mm, the 140-day deflection reached 1/560 of the span. The slab sample with thickness of 180mm exhibited only 60.2% deflection of the one for the 120 mm slab sample.

(2) Under the condition of single-sided confinement, the shrinkage distribution of recycled coarse aggregate concrete along the depth was approximately linear. Its non-uniform shrinkage gradient increased with time and decreased with increasing slab thickness. Moreover, the variation of the non-uniform shrinkage gradient with the thickness of the plate was consistent with the variation of the deflection for the full-scale samples.

(3) When the EC2 specification was used to predict the shrinkage of the slab surface under single-sided confinement condition, the current models greatly underestimated the shrinkage values. It was suggested that the prediction of the shrinkage value of the top surface of the concrete under the condition
of single-sided confinement can be selected according to the nominal size under the condition of double-sided open, and multiplied by an amplification factor of 1.2.

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