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Experimental Investigation of Properties of Concrete Containing Recycled Construction Wastes

Abstract

This research focused on investigating the effects of recycled aggregates on the material properties of concrete and the structural performance of reinforced concrete beams. Two different sources of recycled aggregates, crushed red bricks and demolished concrete, collected from local construction and demolition wastes, were analysed. The pre-wetting method was applied to recycled coarse aggregates aiming to study its effects on concrete specimens. Experimental results assisted by regression analysis revealed that the pre-wetting method could minimize the negative effects caused by recycled aggregate itself on the concrete slump and compressive strength test results. Pre-wetting method was also found improving the dynamic modulus of elasticity for concrete specimens. Adding supplementary cementitious materials was not as effective as the pre-wetting method in enhancing concrete slump, Ultrasonic Pulse Velocity (UPV), strength, or dynamic modulus of elasticity. The reduction of concrete UPV and compressive strength caused by recycled aggregates were more significant in the early curing age. Flexural tests on reinforced concrete beams indicated that although adding recycled concrete aggregates did not significantly change the beam failure load, the ultimate deformation of reinforced concrete beams was reduced by displaying more brittle failure behavior. It was indicated that the failure mode of beam was changed from flexural to shear, inferring that shear capacity of beam with RCA was reduced. Future research directions were proposed focusing on the durability studies of concrete members containing recycled aggregates especially when the pre-wetting method was applied.

Keywords

Recycled aggregates; concrete mixture design; concrete properties; structural test; regression analysis;

1. Introduction

Urbanization in rapidly developing countries (e.g., China) is generating a tremendous amount of construction and demolition (C&D) waste. Recycling of concrete waste has become a solution to treat the large amount of C&D wastes generated, to save natural resources for concrete production, and to protect the urban environment [1,2]. Besides concrete wastes, brick is another major category of C&D wastes in some developing countries such as Bangladesh [3] that has been studied in its application as recycled aggregate in concrete production.

Although Limbachiya et al. [4] claimed that 30% replacement of recycled concrete aggregate (RCA) to natural aggregate (NA) should not significantly affect concrete properties such as strength, there has been limited studies conducting a more comprehensive evaluation of RCA’s effects on concrete quality covering both material properties and structural performance. Oikonomou [5] identified that one barrier of recycling and reusing construction wastes was the unknown source of old concrete which led to uncertainty in the suitability of recycled aggregates for new concrete production. Meyer [6] also indicated that the variety of recycled aggregates from different sources might cause variations in concrete quality. An earlier study [7] indicated that the old concrete from different local C&D waste sources (e.g., pavement demolition and reinforced concrete building demolition) did not cause significantly different concrete properties in terms of slump, ultrasonic pulse velocity (UPV), and the 28-day compressive strength. To continue the study of Jin et al. [7], this research combined different sources of old concrete collected from multiple local C&D sites in Ningbo China, and divided the recycled construction wastes into two major categories: old concrete and red bricks. Accordingly, two types of recycled aggregates, RCA and recycled red brick aggregate (RRBA) were adopted to partly replace NA at replacement rates of 30%. Both recycled coarse and fine aggregates were adopted in the concrete mixture design for this research.

It was previously identified that recycled aggregate could cause negative effects in multiple concrete properties, such as workability, strength, durability, and energy capacity [8-13]. Proper mixture design to reduce these negative effects of recycled aggregates in concrete properties has been attempted by multiple studies [14-17]. Inspired by Expanded Shale, Clay & Slate Institute [18] that introduced the properties of lightweight aggregates, and by Famili et al. [19] and Renolds et al. [20] who used lightweight aggregates as an internal curing agent in concrete, the researchers were motivated to apply the "internal curing" theory from lightweight aggregate concrete to recycled aggregate concrete (RAC), and to explore whether the pre-wetting treatment to recycled aggregates could also enhance concrete properties, as lightweight aggregate did [21]. As stated by Li [22], the ultimate goal for using RAC is to adapt it as the structural material. Structural tests on reinforced concrete beams were performed to evaluate the effects of recycled aggregates on the beam loading capacity, failure mode and deflection.

A review of existing studies (e.g., Limbachiya et al.[4]) on RAC revealed that there has been (1) a lack of comprehensive evaluation of RAC covering both materials and structural tests; (2) limited research of applying some easy treatment methods to recycled aggregates to compensate for its inferior quality; and (3) limited research of comparing recycled aggregates from different sources in terms of their effects on concrete properties, especially how the recycled aggregate property (e.g., water absorption rate) affects the quality of concrete.

The study contributed to the existing knowledge by: 1) applying pre-wetting method to recycled coarse aggregates to make up the lower concrete quality caused by recycled aggregate itself; 2) extending from previous studies such as those reviewed by Li [23] by exploring multiple properties (e.g., Ultrasonic Pulse Velocity or

UPV) of concrete specimens containing recycled ingredients; 3) comparing RRBA and RCA in terms of their effects on the concrete properties; and 4) gaining a comprehensive picture of the effects of recycled aggregates on the concrete properties from both material and structural perspectives, especially by extending previous studies of mainly material tests to structural tests, in order to gain a more holistic understanding of how recycled aggregate affects concrete's performance.

2. Materials and Methods

The experimental study of RAC properties consisted of concrete specimen tests and structural tests on reinforced concrete beams. All relevant standards and specifications involved in this study are listed in Table 1.

<Insert Table 1>

2.1. Material Preparation and Recycled Aggregate Production

2.1.1. Cementitious materials

In this study, Type 42.5 commercial Portland cement conforming to Chinese Standards *Common Portland Cement GB175-2007* [36] was used. Class II fly ash following Chinese Standard *Fly Ash Used for Cement and Concrete GB/T1596* [37], and silica fume conforming to Chinese Standard *Silica Fume Used for Concrete GB/T18736* [38] were used as the supplementary cementitious materials (SCMs).

2.1.2. Aggregate production process and size selection

Coarse aggregates in the size ranging from 4.75mm to 9.5mm were ordered as the natural aggregates (NA) in this study. Recycled aggregates from two major sources (i.e., old concrete and red bricks) were collected from demolition sites in Ningbo City, China. Fig. 1 shows some local demolition sites that generated C&D wastes.

<Insert Fig. 1>

Old concrete and red bricks were separated and crushed in jaw crusher. The debris was then put into sieve machines to be separated into different size ranges, including 0-1.18 mm, 1.18-2.63 mm, 4.75-9.5 mm, 9.5 -19.0 mm, and larger than 19.0 mm, etc. The recycled aggregate with size ranging from 4.75-9.5 mm was adopted as the recycled coarse aggregate in the experimental study, to be consistent with the size of NA ordered. Fine debris with size ranging from 0-1.18 mm was adopted as the recycled fine aggregate. The fineness modulus for recycled concrete aggregates (RCA) and recycled red brick aggregates (RRBA), was tested at 1.850 and 2.025 respectively following ASTM C136 [25]. The fineness modulus of natural sand was equal to 1.917, close to the size of recycled fine aggregates. The four different types of recycled aggregates from RCA and RRBA are displayed in Fig. 2.

<Insert Fig. 2>

2.1.3. *Reinforcement details*

There are two types of steel rebars used in the experimental tests. All types of beams were designed with four stirrups and two top rebars sized at R8. Here R8 is round mild steel with the diameter of 8 mm. Two major types of beams were designed targeting on the flexural failure and shear failure respectively. Two T14 rebars were used for the flexural beam, and two T16 rebars were designed for the shear-failure beams as shown in Fig. 3, which also displays the beam section's reinforcement details. All longitudinal rebars had characteristic yielding strength of 500 MPa. T14 and T16 are high yield strength ribbed steel with diameters of 14 mm and 16 mm, respectively.

<Insert Fig. 3>

2.2. *Different properties of ingredients*

The density, water absorption, and Los Angeles (LA) abrasion tests were conducted on the recycled aggregates. Table 2 lists the specific gravities of all aggregate materials in this study.

<Insert Table 2>

It can be found from Table 2 that recycled aggregates had lower density or specific gravity compared to NA, due to the internal voids within recycled aggregate particles or mortar attached to the surface of RCA. RRBA had lowest density among all types of aggregates.

Following ASTM 127[28], the full-wet mass, saturated-surface-dry mass, and oven-dry mass of samples were measured. The total moisture rates, water absorption rate, and surface moisture were calculated. These test results are listed in Table 3.

<Insert Table 3>

RRBA showed the highest water absorption rate among the three major types of coarse aggregates in Table 3. The water absorption rate of RRBA (i.e., nearly 20%) was comparable or even higher than that of general lightweight aggregate described in ESCSI [18]. The water absorption capacity of RCA was also fairly higher than that of NA.

LA abrasion tests were performed to quantify the toughness and resistance to crushing of aggregates. Using the MH-II LA abrasion machine following ASTM C131/C131M [30], the tests results were obtained as seen in Table 4.

<Insert Table 4 >

Table 4 shows that RCA had comparable LA abrasion value to that of NA, and RRBA had lower abrasion resistance.

2.3. Concrete mixture design

The mixture design of the experimental study adopted the water-to-cement ratio of 0.41 following ACI 211.2 [26]. The mixture design details of concrete batches are listed in Table 5.

<Insert Table 5 >

According to Table 5, the control group which adopted NA as the sole coarse aggregate was 800 kg/m^3 of concrete produced. In other batches when recycled aggregates were included in the mixture design, 30% of coarse aggregates and/or sand were replaced by RCA or RRBA by weight. The rationale of adopting 30% replacement rate of RA to NA was based on previous studies including Limbachiya et al.[4] and Xu et al [39]. According to Limbachiya et al. [4], substitution rate at or below 30% did not cause significant reductions to the concrete strength. It was found by Xu et al [39] that the 30% substitution rate of RA to NA improved or optimized the compressive strength of concrete. Since 30% was identified as the critical point above which the replacement of RA to NA caused more significant changes in the mechanical properties of concrete, this study adopted 30% as the substitution rate for RBA and RCA to replace NA to explore the effect of RA on the concrete properties. The findings allow further comparison between this study and previous research. Detailed descriptions of all concrete cylinder and prism batches manufactured in this study are provided in Table 6.

<Insert Table 6>

The pre-wetting method applied to coarse RCA and RRBA followed the procedure to immerse dry coarse RCA or RRBA in water for 24 hours and then dry the aggregates surface in the follow-up four-hour process of removing surface moisture in the laboratory condition right before concrete mixing. It is worth noticing that 30% pre-wetted recycled coarse aggregate in Table 6 did not mean the 30% replacement by weight to NA. Instead, the pre-wetted recycled aggregates had the same volume as in the case of dry recycled aggregate. In other words, the weight of internal moisture contained in pre-wetted recycled aggregates was not counted in the concrete mixture design.

According to Table 6, three major categories of concrete batches were designed in this study besides the control group. These categories included concrete containing recycled RRBA (Batches 1a, 1b, 1c, and 1d), concrete mixed with RCA (Batches 2a, 2b, 2c, and 2d), and concrete mixed with RCA and SCMs (i.e., fly ash and silica fume). Concrete batches with RCA or RBBA, each category containing four different mixtures or treating methods of recycled coarse aggregates, allow the comparison of concrete properties between those with and without recycled fine aggregate, and those with and without applying pre-wetting treatment to recycled coarse aggregates.

Besides the concrete cylinder and prism batches, four different types of reinforced concrete beams were also cast to study the effects of recycled aggregates on the flexural behaviour of beams. Table 7 describes the reinforcement type and concrete mixtures in the four types of beam.

<Insert Table 7>

The reinforcement details can be found in Fig. 3. Beam types (i.e., 4a and b, 5a and b) are distinguished by either longitudinal rebar sizes in the tension zone or concrete mixture design according to Table 7. Each type of beam was cast with two identical samples for obtaining the average values of beam flexural performance related data (e.g., failure load). The beam test scheme was designed with RCA and SCMs included in the concrete mixture, aiming to reduce the carbon footprint within both aggregate and cementitious materials.

2.4. Laboratory tests of concrete specimens

The procedure of concrete mixing and curing followed ASTM C31/C31M [27]. The 150 x 300 mm^2 cylinders, 400 x 100 x 100 mm^3 prisms, and 1677 x 203 x 102 mm^3 beams were cast in steel formworks.

The compressive strength tests and Ultrasonic Pulse Velocity (UPV) tests of the cylinder batches were carried out on the 7th, 14th and 28th days after water curing and dried under the same laboratory condition. The dynamic beam tests were performed on Day 28. The test facilities for UPV, compressive strength, and Erudite test for dynamic modulus of elasticity are shown in Fig. 4.

<Insert Fig. 4>

The Portable Ultrasonic Non-detective Digital Indicating Tester (PUNDIT), as shown in Fig. 4(a), was adopted to examine the concrete quality using the pulse velocity method. A faster pulse passing through the cylinder as shown in Fig. 4(a) indicates fewer cracks and defects in concrete, and hence infers a better concrete quality. Erudite test, a non-destructive test primarily used for quality control as shown in Fig. 4(c), generates the dynamic elasticity modulus of prisms by resonant frequency test system. The test was conducted by following ASTM C215 [33] and the longitudinal resonant frequency was measured automatically. ASTM C215 [33] specified the equation to compute Dynamic elasticity modulus (E) as in Equation (1)

$$E = \frac{4 * L}{b * t} * M * n^2 \qquad \text{Equation (1)}$$

where:

M = mass of specimen, kg,

n = fundamental transverse frequency, Hz,

L = length of prism, m.

t, b = dimensions of cross section of prism, m.

Fig. 5 shows the setup for four-point beam flexural test. The dial gauge was also installed at the beam mid-span to measure the deflection during the loading process.

<Insert Fig. 5>

3. Results

The experimental results include slump, densities, Ultrasonic Pulse Velocity (UPV), compressive strength, dynamic modulus of elasticity, and beam flexural performance.

3.1. Slump and densities

Ten different concrete batches listed in Table 6 were tested for their fresh concrete slump and densities. The comparison of slump and densities among the ten different batches can be found in Fig. 6.

<Insert Fig. 6>

It should be noticed that the slump test was performed right after fresh concrete was produced from the laboratory mixer. The slump values after a period of time were not available. It can be found from Fig. 6 that 30% replacement of NA by either RCA or RRBA resulted in a significant slump loss. It has been known that either the mortar attached to the surface of RCA or the internal voids within recycled aggregates absorb water in the concrete mixture process, hence reducing the workability of concrete. However, the slump test results of Batches 1c and 2c shown in Fig. 6 also indicate that the pre-wetting method could prevent the slump loss. It is inferred that the pre-saturated recycled aggregate, with its internal voids filled with moisture, does not continue to absorb extra water from the fresh concrete mixture. Therefore, pre-saturation could prevent workability loss. Nevertheless, concrete had significant slump reduction when 30% of sand was replaced by recycled fine aggregate despite that the recycled coarse aggregate was pre-wetted. This was because the recycled fine aggregates, with their internal voids, absorbed water from the concrete mixture. It should also be noticed that Fig. 6(a) does not include Batches 1b and 2b, which represent both coarse and fine recycled aggregates but without applying the pre-wetting method. This is because Batches 1b and 2b were found to have a little workability if no further water was added. Dry RCA with certain SCMs (i.e., 15% of fly ash and 5% silica fume) still resulted in a significant slump decrease. Therefore, it could be indicated that pre-wetting was an effective method in maintaining the concrete workability when recycled aggregate was used in concrete mixture. In comparison, using SCMs such as fly ash within concrete containing RCA did not compensate for the slump loss caused by the recycled aggregates.

Densities of all concrete batches ranged from 2260 and 2400 kg/m^3. Due to the lower density of recycled aggregates, concrete batches with recycled contents displayed slightly lower density. Concrete batches with 30% replacement rate of coarse RRBA resulted in around 4% reduction in density, and 30% replacements for both NA and sand with RRBAs resulted in around 6% density decrease. Using RCA for up to 30% replacement rate to NA caused only 2% density reduction. The reduction was increased to 3% when both 30% of NA and sand were replaced by RCAs.

3.2. Hardened concrete properties

3.2.1. Ultrasonic Pulse Velocity (UPV) test

The velocities (m/s) of concrete batches after 7, 14 and 28 days of curing are displayed in Fig. 7.

<Insert Fig. 7>

The UPV test results for all concrete batches, as displayed in Fig. 7, ranged from 4231 to 4552 m/s. Although there were not significant changes of velocities within the concrete cylinders when 30% of NA was replaced by recycled aggregates, especially only when 30% of NA was replaced by RCA, the general trend of reduction in UPVs caused by recycled aggregates could still be identified. The reduction of UPV due to recycled aggregate could be explained by the internal air contained in the voids of aggregates as an ultrasonic wave travels more slowly in the air or discontinuous internal structure caused by recycled aggregates. This reduction is more significant when recycled aggregates have a higher percentage of voids. This was proved by the experimental observation that RRBA caused a higher reduction of UPV in concrete specimen compared to RCA, as RRBA contained the higher void volume than RCA. Adding 30% of fine recycled aggregate caused further reduction of UPVs due to the internal voids contained in the recycled fine aggregates. The UPV values of all batches increased with the curing age. The UPV reduction caused by recycled aggregates was more significant in early ages (e.g., Day 7). As the concrete age increased, the UPV of concrete batches containing recycled contents was more comparable to that of the control group. The observation of UPV change in Fig. 7 could be further quantified through the regression analysis by linking the dependent variable (i.e., UPV) and six independent variables defined in Table 8.

<Insert Table 8>

The linear regression analysis was conducted in Minitab statistics software, to explore the statistical significance between UPV and each of these six independent variables. Table 9 summarizes the linear regression analysis.

<Insert Table 9>

Table 9 provides the quantitative analysis of the effects of each independent variable on the UPV value. Overall 73.2% of the UPV value could be explained by the six defined independent variables, with the overall *p* value at 0.000. Based on the 5% level of significance, it could be further identified that the pre-wetting method significantly reduced the UPV value. The coarse RRBA tended to cause higher reduction of UPV compared to RCA, based on its higher negative value of the coefficient and *t* value, as well as the lower *p* value, which was consistent with the observations from Fig. 6.

3.2.2. Dynamic Modulus of elasticity

The results of dynamic modulus of elasticity tests for the ten concrete batches on Day 28 are displayed in Fig. 8.

<Insert Fig. 8>

It can be found from Fig. 8 that recycled aggregates caused some reduction in dynamic modulus of elasticity. The highest reduction of close to 20% occurred when both NA and sand were partly replaced by recycled RRBAs. The second highest reduction of 15% happened when both NA and sand were partly replaced by RCAs. Somewhat similar to the effects of recycled aggregates on the UPV and the compressive strength, RRBA caused a more significant reduction in the dynamic modulus of elasticity. Pre-wetting method was found improving the dynamic modulus of elasticity for concrete containing either RRBA or RCA, although the dynamic modulus of elasticity of concrete with pre-wetted recycled aggregates was still lower than that of the control group. Adding SCMs (i.e., 15% of fly ash and 5% of silica fume) did not improve the dynamic modulus of elasticity for concrete containing coarse RCA.

3.2.3. Compressive strength

The compressive strength of concrete cylinders at three different curing ages (i.e., 7, 14, and 28 days) was tested. Fig. 9 allows the comparison of the tests results obtained from ten batches.

<Insert Fig. 9>

Somewhat similar to the effects in UPV, recycled aggregates also caused a more significant reduction of the compressive strength in the early age. The longer term (e.g., Day 28) compressive strength of concrete specimens with recycled content turned more comparable to the control group. For example, the compressive strength of the concrete with 30% RRBA was reduced by 25% on Day 7, but the strength reduction percentage was decreased to 16% on Day 28. Compared to RCA, RRBA also caused a higher reduction in the compressive strength. When

30% RCA instead of RRBA was used, the reduction percentages were only 8% and 5% on Day 7 and Day 28, respectively.

Fig. 9 also shows that the pre-wetting method could make up for the loss of concrete compressive strength caused by recycled aggregates, and the 28-day strength could be even slightly higher than that of the control group. On Day 28, the enhancement of compressive strength through pre-wetting coarse recycled aggregate was more evident compared to that through adding SCMs.

Using the linear regression approach to study the effects of the six independent variables in compressive strength, the statistical significances are presented in Table 10.

<Insert Table 10>

The coarse RRBA had a more significant impact on compressive strength than coarse RCA, according to the corresponding higher t value and F value, as well as the significant p value. This observation was consistent to that in Fig. 9. The more negative impact of coarse RRBA to concrete strength compared to RCA could be explained by the higher void volume and the lower LA abrasion resistance in RRBA, as identified by Table 3 and Table 4. Both Fig. 9 and Table 10 indicate that the pre-wetting method could significantly improve the compressive strength. No evidence was found that further addition of the fine recycled aggregates decreased the compressive strength of concrete.

3.3. Beam flexural test

3.3.1. Ultimate failure load

Four different types of reinforced concrete beam (i.e., Types 4 and b, 5a and b) defined in Table 7 were tested to their ultimate failure load. The design failure loads based on the 28-day concrete compressive strength were also calculated following EC2 [40] and are presented in Fig. 10.

<Insert Fig. 10>

It can be found from Fig. 10 that the actual failure loads for all four types of reinforced concrete beams met the calculated design capacity. In comparison to beam types 4a and 4b, where no recycled aggregates were added, beam types 5a and 5b displayed consistent load capacities.

3.3.2. Failure mode

The failure modes of the four types of beams were also investigated. Pictures of the beam cracking patterns at failure are displayed in Fig.11.

<Insert Fig. 11>

It can be seen in Fig.11 that RC beam types 4a and 4b behaved according to their original design. Beam Type 4a displayed a ductile flexural failure mode. However, beam Type 4b with the higher longitudinal reinforcement ratio, showed shear failure with inclined cracks. It can also be observed from Fig.11 that the failure mode changed from ductile flexural failure in Beam Type 4a to brittle shear failure in Beam 5a even though the concrete strengths and ultimate failure loads were similar in both beams.

3.3.3. Deflection

Besides the loading capacity measurement and failure mode observations, the flexural beam tests in this study also involved the measurement and analysis of the beam deflection during the whole loading process. Fig.12 describes the displacement of beam mid-span along the whole loading process.

<Insert Fig. 12>

As observed in Fig. 12, Beam 4a, the only type of beam that displayed ductile behavior in this study, also displayed a significantly higher deflection of the middle section at failure. Other three types of beams had nearly linear relationships between load and deflection and displayed brittle failure with lower ultimate deflections when reinforcement ratio changed or RCA was added. Among the three types of beams, Beam 4b had a relatively higher mid-section deflection compared to types 5a and 5b. It was indicated that under the shear failure mode, adding RCA could reduce the ultimate beam deflection.

4. Discussion

This experimental study was designed to analyse the effects of recycled aggregates from two main waste resources (i.e., old concrete and red bricks) collected from China’s local construction and demolition sites. The research started from material tests of concrete specimens in terms of slump, density, Ultrasonic Pulse Velocity (UPV), compressive strength, and dynamic modulus of elasticity, and later moved onto structural tests by adopting recycled concrete aggregate (RCA) in reinforcement concrete beams. The material tests of concrete specimens were used to compare the properties of concrete from ten different batches within four major categories: (1) concrete batches mixed with RCAs, (2) batches with recycled red brick aggregates (RRBAs), (3) concrete with RCA and SCMs, and (4) the control batch without recycled contents. Both coarse and fine recycled aggregates were applied in concrete mixture design to replace 30% of NA and sand in certain batches.

It was found that both RRBA and RCA decreased concrete slump, due to their internal voids or extra mortar attached to RCA surface. RRBA, due to its higher internal void volume, caused a higher reduction in concrete slump compared to RCA. The pre-wetting method turned out more effective than adding SCMs (i.e., fly ash) in minimizing the slump loss caused by recycled aggregates. The pre-wetting method was also found effective in improving the concrete strength, according to the observations from Fig.7 and the linear regression based statistical analysis presented in Table 10. However, the pre-wetting method did not prove its enhancement to concrete UPV test results according to the consistent results obtained in Fig. 8 and Table 9. The regression statistical approach served as the quantification tool to identify that RRBA caused more significant reductions in both UPV and the compressive strength of concrete compared to RCA.

Both Fig. 6 and Fig. 7 indicated that concrete containing recycled contents had inferior UPV and the compressive strength compared to the control batch in early curing age (e.g., Day 7). However, these hardened properties tended to be more comparable as curing age increased. Overall, adding extra recycled fine aggregates caused significant slump loss despite that the coarse recycled aggregate was pre-wetted. However, adding recycled fine aggregate did not have any significantly negative effect on the compressive strength. The recycled fine aggregates (both RRBA and RCA) were found causing further reductions in concrete dynamic modulus of elasticity after 28 days of curing. In contrast, the pre-wetting method or SCMs did not cause any significant changes in the dynamic modulus of elasticity.

The structural testing of the reinforced concrete beams was included as an extension from the material study of plain concrete containing recycled aggregates. RCA and SCMs (i.e., fly ash and silica fume) were applied in the concrete mixture to reduce the carbon footprint of concrete. Compared to the control group beams without RCA or SCM, the loading bearing capacities of beams containing recycled contents were not significantly affected and met the design load capacity requirements. However, the impacts of RCA on the flexural behaviour of reinforced concrete beams could be found in terms of failure mode and deflection. RCA was found changing the failure mode of beams from ductile flexural cracking to more brittle shear diagonal cracking. RCA was found decreasing the deflections of beam mid-sections as well. The load-deflection curve for beams containing RCA displayed a generally linear trend, without extended deflection after the beams reached their loading capacity. The negative effect of RCA on the failure mode and mid-section deflection of beams could be caused by the bonding between aggregates and the reinforcement in concrete structures. The extra mortar attached to RCA surface might result in a different bond behavior between aggregates and rebars, leading to further influence on the structural performance of reinforced concrete beams.

6. Conclusions

This research aimed to investigate the effects of recycled aggregates on concrete properties in a more comprehensive approach by conducting both material tests on plain concrete and structural tests on reinforced concrete beams. Recycled concrete aggregate and recycled red brick aggregates were generated from C&D waste collected from local demolition sites in Ningbo, China. The pre-wetting method was adopted to recycled coarse aggregates in concrete mixing. Some conclusions are drawn based on the laboratory test results:

- The slump loss caused by recycled coarse aggregates could be compensated by introducing the pre-wetting method. However, further addition of the recycled fine aggregate reduced the slump. Compared to SCM additives, such as fly ash, the pre-wetting method was found more effective in maintaining the slump in concrete containing recycled aggregates.
- The pre-wetting method was found effective in improving concrete compressive strength, especially after 14 days of curing. However, no significant effects of the pre-wetting method in the concrete Ultrasonic Pulse Velocity (UPV) was found.
- Recycled aggregates caused more reduction in early curing ages for both UPV and compressive strength. However, the longer term (e.g., Day 28) UPV and compressive strength of concrete containing recycled aggregates turned out more comparable to that of the control batch.
- Both bar chart observation and regression statistical analysis indicated that the recycled red brick aggregates caused a more significant loss in UPV and compressive strength, compared to recycled concrete aggregate. This could be due to the higher water absorption rate, lower LA abrasion resistance, or other properties of recycled aggregates. Future study could focus on linking these recycled aggregate properties into corresponding concrete quality.
- Using recycled fine aggregate besides recycled coarse aggregate generally caused more negative effects in concrete, including the reduction of the dynamic modulus of elasticity. Pre-wetting recycled coarse aggregate could also prevent the further reduction of dynamic modulus of elasticity caused by recycled fine aggregate. In comparison, SCMs (i.e., fly ash and silica fume) did not have such positive effects in concrete dynamic modulus of elasticity.
- Although recycled aggregate concrete with SCMs incorporated in concrete mixture might not cause significant changes in the failure load of reinforced concrete beams by meeting the design capacity requirement, the ultimate deformation of beams could be reduced due to either changed failure mode or decreased mid-section deflection. Further investigation of the reduced ductility of reinforced concrete beams caused by recycled aggregates is needed.

Based on the current research findings, future research will focus on investigating the durability of concrete specimens containing different types of recycled aggregates, reinforced concrete beams containing recycled content subject to sustained loading and corrosion, and the effect of pre-wetting method in the flexural performance of concrete beams containing recycled aggregates.

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Title Page

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Table 1. Standards involved in this study

Laboratory activity	Standard	Description
Processing old concrete into recycled concrete aggregate	ACI 555R-01 [24]	Removal and Reuse of Hardened Concrete
Fineness modulus test	ASTM C136-06 [25]	Sieve analysis of fine and coarse aggregates
Concrete mixture design	ACI 211.2 [26]	Standard practice for selecting proportions for normal, heavyweight, and mass concrete
Concrete mixing	ASTM C31/C31M [27]	Standard practice for making and curing concrete test specimens
Density & Absorption test for coarse and fine aggregates	ASTM C127 [28] /C128 [29]	Specific gravity and absorption
Abrasion test of aggregates	ASTM C131/C131M [30]	Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine
Slump test	ASTM C143/C143M [31]	Standard test method for slump of hydraulic-cement concrete
Ultrasonic Pulse Velocity (UPV) test	ASTM C597 [32]	Standard test method for pulse velocity through concrete
Test of dynamic modulus of elasticity	ASTM C215 [33]	Standard test method for fundamental transverse, longitudinal, and torsional resonant frequencies
Compressive strength test	ASTM C39 [34]	Standard test method for compressive strength of cylindrical concrete specimens
Flexural strength test	ASTM D6272 [35]	Standard test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials by four-point bending

Table 2. Specific gravity of different aggregate materials

Aggregate	**Sand**	**NA**[*]	**Coarse RCA**	**Fine RCA**	**Coarse RRBA**	**Fine RRBA**
Specific gravity	2.260	2.641	2.485	1.890	1.950	1.769

*: NA stands for natural coarse aggregate

Table 3. Water absorption related results of coarse aggregates

Type of coarse aggregate	NA	RCA	RRBA
Total moisture (%)	6.28	15.02	28.68
Water absorption (%)	1.12	6.41	19.43
Surface moisture (%)	5.16	8.61	9.25

Table 4. LA Abrasion results of NA and RA

Material	**NA**	**RCA**	**RRBA**
LA abrasion (%)	39.46	36.20	56.23

Table 5. Target concrete mixture design for non-air-entrained concrete batches

w/c ratio	**Water (kg/m^3)**	**Cementitious materials (kg/m^3)**	**Coarse aggregate (kg/m^3)**	**Sand (kg/m^3)**
0.41	228	557	800	692

Table 6. Type of concrete cylinder and prism batches

Batch	Definition	Description
1	No recycled aggregates applied in concrete mixture design	Control group
1a	Replacing NA with 30% coarse RRBA	30% coarse RRBA
1b	Replacing NA with 30% coarse RRBA + Replacing sand with 30% fine RRBA	30% coarse RRBA+30% fine RRBA
1c	Replacing NA with 30% pre-wetted coarse RRBA	30% pre-wetted coarse RRBA
1d	Replacing NA with 30% pre-wetted coarse RRBA + Replacing natural sand with 30% fine RRBA	30% pre-wetted coarse RRBA+30% fine RRBA
2a	Replacing NA with 30% coarse RCA	30% coarse RCA
2b	Replacing NA with 30% coarse RCA + Replacing natural sand with 30% fine RCA	30% coarse RCA + 30% fine RCA
2c	Replacing NA with 30% pre-wetted coarse RCA	30% pre-wetted coarse RCA
2d	Replacing NA with 30% pre-wetted coarse RCA + Replacing natural sand with 30% fine RCA	30% pre-wetted coarse RCA + 30% fine RCA
3	Replacing NA with 30% coarse RCA+ Replacing Portland cement with 15% fly ash and 5% silica fume by weight	30% RCA +15% FA + 5% SF

Table 7. Type of concrete beam specimens

Type	**Reinforcement**	**Concrete mixture**	**Description**
4a	Top: 2R8 Bottom: 2T14	With solely NA	Medium NA beam
4b	Top: 2R8 Bottom: 2T16	With solely NA	High NA beam
5a	Top: 2R8 Bottom: 2T14	Replacing NA with 30% coarse RCA+ Replacing Portland cement cement with 15% fly ash and 5% silica fume	Medium 30% RCA +15% FA + 5%SF
5b	Top: 2R8 Bottom: 2T16	Replacing NA with 30% coarse RCA+ Replacing Portland cement with 15% fly ash and 5% silica fume	High 30% RCA +15% FA + 5%SF

Table 8. Definition of independent variables in concrete mixture design

Independent variable	**Description**	**Attribute**	**Value**
Age	Concrete curing age	Numerical	7, 14, or 28
Coarse RRBA	Replacement of NA by coarse RRBA	Binary	0 or 30%
Fine RRBA	Replacement of sand by fine RRBA	Binary	0 or 30%
Coarse RCA	Replacement of NA by coarse RCA	Binary	0 or 30%
Fine RCA	Replacement of sand by fine RCA	Binary	0 or 30%
Pre-wetting method	Whether RCA is pre-wetted	Binary	0 or 1[*]

[*]: The binary value of 1 in pre-wetting method means recycled coarse aggregate was pre-wetted.

Table 9. Regression analysis for UPV linked to six independent variables within concrete mixture (R^2 = 73.2%, significance value = 0.000, N=27[1])

Independent variable	**Coefficient analysis**		**Analysis of Variance (ANOVA)**	***p* Value**
	Coefficient	***t* Value**	***F* Value**	
Age	9.17	4.37	19.07	**0.000**[2]
Coarse RRBA	-765	-3.28	10.73	**0.004**[2]
Fine RRBA	-111	-0.61	0.37	0.551
Coarse RCA	-214	-0.91	0.84	0.371
Fine RCA	-455	-2.48	6.16	**0.022**[2]
Pre-wetting method	-85	-2.18	4.75	**0.041**[2]

[1]: totally 27 observations formed the data sample, excluding the observation in Batch 3 where SCMs were involved.

[2]: *p* value lower than 0.05 indicates a significant effect of the independent variable in UPV result

Table 10. Regression analysis for compressive strength linked to six independent variables within concrete mixture (R^2 = 82.7%, significance value = 0.000, N=27)

Independent variable	**Coefficient analysis**		**Analysis of Variance (ANOVA)**	***p* Value**
	Coefficient	***t* Value**	***F* Value**	
Age	0.422	8.62	74.25	**0.000***
Coarse RRBA	-20.18	-3.70	13.72	**0.001***
Fine RRBA	8.99	2.10	4.42	**0.048***
Coarse RCA	-7.89	-1.45	2.10	0.163
Fine RCA	-5.38	-1.26	1.58	0.223
Pre-wetting method	2.673	2.95	8.69	**0.008***

*: *p* value lower than 0.05 indicates significant effect of the independent variable in compressive strength

Fig. 1. Recycle sites in Ningbo City

a) Coarse RCA b) Fine RCA c) Coarse RRBA d) Fine RRBA

Fig. 2. Different types of recycled aggregates used in this study

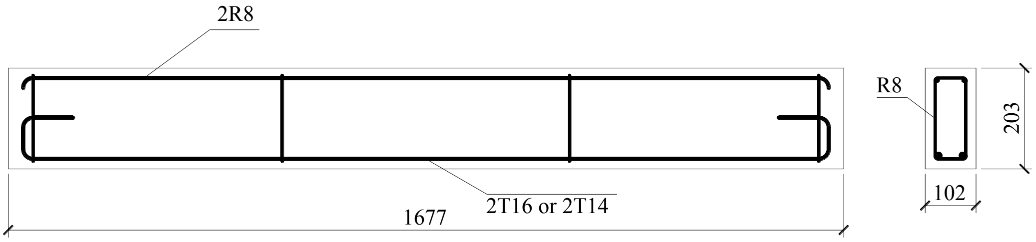


Fig. 3. Reinforcement details of concrete beams with 2 R16 bottom longitudinal rebars (unit: mm)

(a) UPV test

(b) Compressive strength test

(c) Erudite test for dynamic modulus of elasticity

Fig. 4. Tests facilities for concrete cylinders and prisms

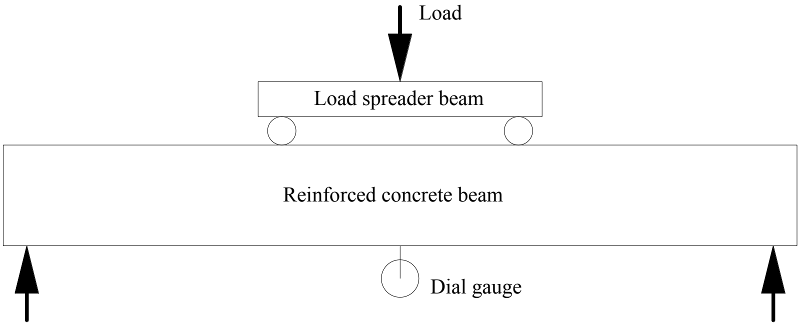
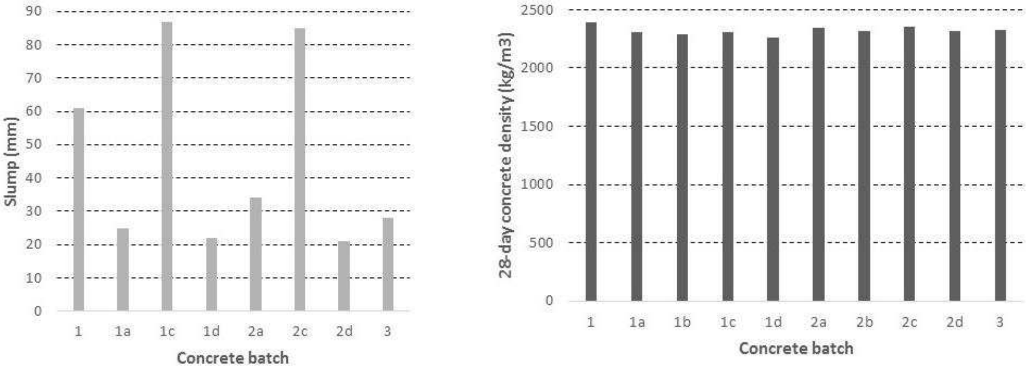


Fig. 5. A schematic view of the setup for a four-point beam flexural test



(a) Slump of concrete batches (b) Densities of different concrete batches

Fig. 6. Slump and density comparison among concrete batches

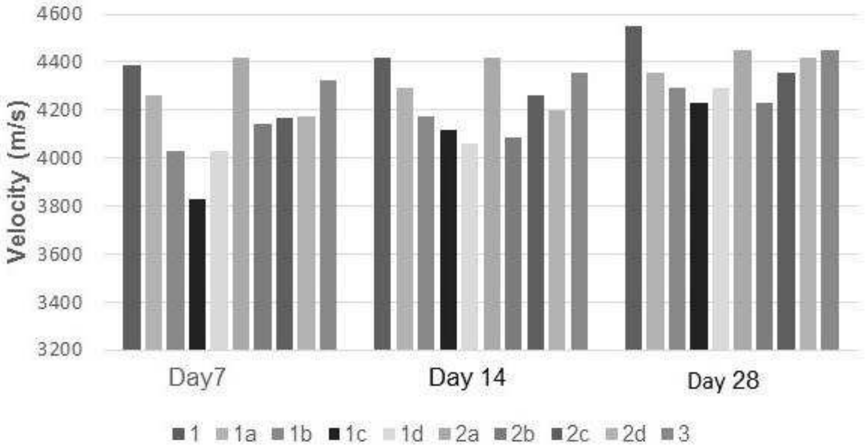


Fig.7. UPV test results of concrete batches in different curing ages

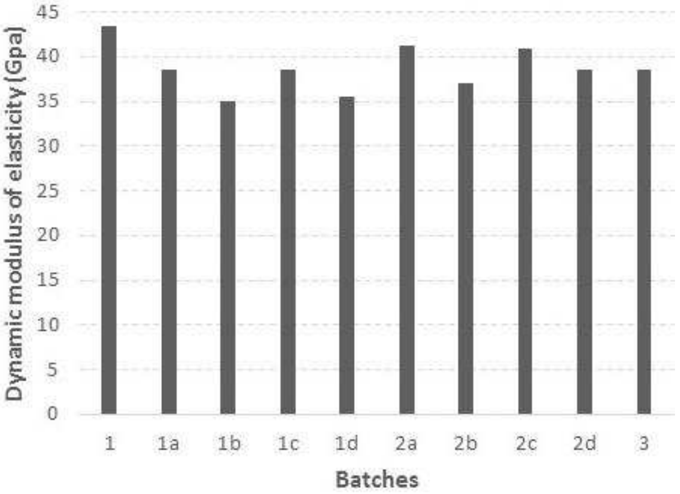


Fig.8. Comparison of dynamic modulus of elasticity among different batches on Day 28

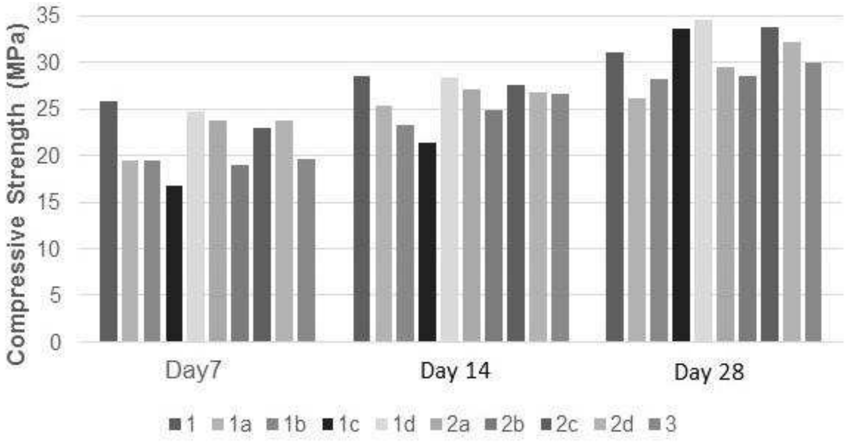


Fig.9. Compressive strength test results of concrete batches in different curing ages

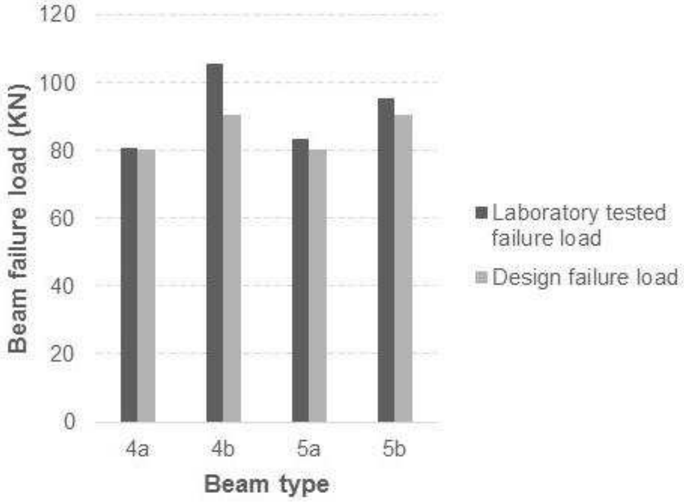


Fig.10. Failure loads of reinforced concrete beams

Beam 4a

Beam 4b

Beam 5a

Beam 5b

Fig.11. Crack patterns upon failure for four different beam types

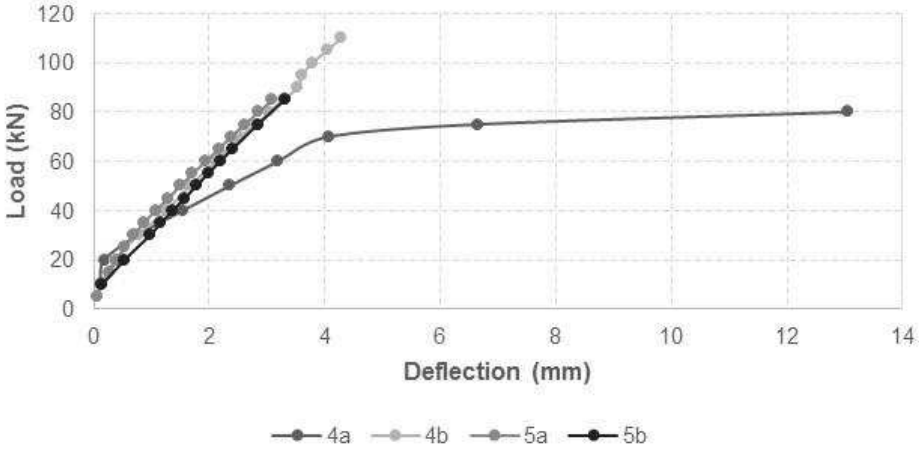


Fig. 12. Load- versus mid-span displacement of four different types of beams