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# Experimental study on the failure mechanism of recycled concrete

Qiong Liu [a], Jianzhuang Xiao [a,*], Zhihui Sun [b]

[a] Department of Building Engineering, Tongji University, Shanghai, 200092, PR China
[b] Department of Civil & Environmental Engineering, University of Louisville, Louisville, KY 40292, USA

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ABSTRACT

In this study, Young's modulus, strength, and peak strain of recycled concrete under both compressive and tensile loading were experimentally studied to understand its failure mechanism. Due to the different colors of natural aggregates, old hardened mortar, new hardened mortar, and interfacial transition zone (ITZ), the quantity and the distribution of each phase were analyzed by images processing and analysis of cut sections. With the tests, the failure processes and crack situation of the recycled concrete under tensile and compressive loadings were illustrated. It was found that some mechanical properties of recycled concrete are similar to those of mortar, for instance, lower Young's modulus, higher peak strain and more brittleness, due to a larger volume content of both new and old hardened mortar. When compared with old hardened mortar, new hardened mortar has more significant influence on both the strength and the Young's modulus of recycled concrete.



## 1. Introduction

Recycled concrete is an environmental green construction material, which uses processed or rather crushed waste concrete as coarse aggregates. Compared with conventional concrete, recycled concrete normally has a lower strength, lower elastic modulus, and a higher peak strain [1–4]. Although many investigations have been carried out to study its strength, modulus, durability, etc., the fundamental failure mechanism of recycled concrete is still not clear.

The waste concrete that is used in the production of recycled aggregates is called parent concrete in this paper. Researchers found that the properties of recycled concrete were greatly affected by the properties of the parent concrete used. Padmini [5], Xiao and Du [6] have pre-tested the elastic modulus and strength of the parent concrete before using it to make recycled concrete. Their experiments showed that for a given water-to-cement ratio, the recycled concrete containing parent concrete with better quality had a higher compressive strength and a higher Young's modulus.

From the material point of view, recycled concrete can be regarded as a four-phase composite that includes natural aggregates (NA), old hardened mortar (OM), new hardened mortar (NM) and interfacial transition zone (ITZ). The differences in quality and quantity of each phase will cause the distinctness of the mechanical properties of recycled concrete.

ITZ is regarded as the weakest link in concrete by most researchers [7]. For recycled concrete, there are three types of ITZ: between NA and OM, between NA and NM and between OM and NM. To what degree do ITZs, NM and OM influence the mechanical properties of recycled concrete? Answers to these questions are still not clear. This leads to the objective of this study, which is to study the failure mechanism of recycled concrete by investigating the influences of NM and its parent concrete.

In this study, intensive laboratory tests were conducted to obtain the compressive and tensile behaviors and to analyze influences of each phase on mechanical properties of recycled concrete, such as strength and Young's modulus. Two types of recycled aggregates were produced from two different strength grades of parent concrete.

## 2. Experimental descriptions

### 2.1. Design of experiments

In order to control the properties of parent concrete, concrete was first mixed with white cement, black natural aggregates, river sand and water. Two strength grades (i.e., C20 and C30) were prepared by using different mix proportions as listed in Table 1. Specimens were made to conduct both the tensile and compressive strength tests for the parent concrete. In addition, six cube specimens (150×150×150 mm) were prepared for crushing and sieving to be used as recycled coarse aggregates. The recycled coarse aggregates made from C20 and C30 concrete were named as RA20 and RA30, respectively. Because it is necessary to know the mechanical properties of mortars (the OM phase in recycled concrete) for the analysis purposes, mortars with the same mix proportions as concrete without coarse aggregates were also made to conduct compressive and tensile strength tests.

* Corresponding author. Tel.: +86 21 65982787; fax: +86 21 65986345.
*E-mail address:* jzx@tongji.edu.cn (J. Xiao).

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**Table 1**
The mix proportions of the concrete.

| | Cement | Sand | Coarse aggregate | Water |
|---|---|---|---|---|
| C20 | 1.000 | 1.989 | 3.693 | 0.574 |
| C30 | 1.000 | 1.395 | 2.591 | 0.429 |

**Table 2**
The gradation of the natural coarse aggregate.

| Size of test sieve (mm) | 5 | 10 | 16.5 | 20 | 25 |
|---|---|---|---|---|---|
| Percentage passing (%) | 0 | 17.6 | 63.4 | 89 | 100 |

When making recycled concrete, grey cement, river sand, water and the crushed parent concrete were used. The details of mix proportions are also given in Table 1. The four recycled concretes were named as RC20–20, RC20–30, RC30–20, and RC30–30, respectively. For illustration purposes, RC20–20, where RC states for recycled concrete, the first "20" means the recycled coarse aggregates that were used are from the C20 parent concrete, and the second "20" represents the objective strength grade of the newly made recycled concrete. Specimens were cast for both compressive and tensile tests for each concrete. To obtain the properties of NM in recycled concrete, the specimens of grey mortar were also cast for strength tests.

To obtain the strength of ITZ in recycled concrete, direct tension tests were first applied to the parent concrete. Tensile specimens of recycled concrete were then made by casting new concrete together with one of the two broken pieces of the parent concrete. By doing this, a new ITZ formed between the newly cast concrete and the cross-sectional area of the parent concrete. These newly made specimens were then tested for tensile strength. The stress at which the specimen failed was approximate to the ITZ strength. The whole experiment process is drawn and described in Fig. 1.

### 2.2. Materials

In this study, white Portland cement was used in casting of parent concrete, which was then tested and crushed to be used as recycled aggregates. The gradation of the black natural coarse aggregates was given in Table 2. The specific gravity of the natural coarse aggregates was 2.79. The recycled aggregates, as shown in Fig. 2, were attained from crushing and sieving cube specimens of parent concrete and their gradations are given in Table 3.

Portland cement with grey color was used to make recycled concrete. Due to the raw materials that used, the colors of the natural aggregates, the old mortar and the new mortar were black, white and grey, respectively. This would assist the identification of each phase in recycled concrete during the image analysis processing of this study.

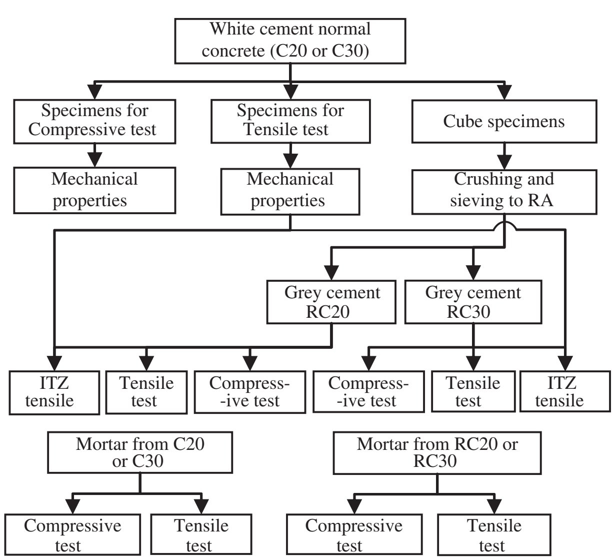


**Fig. 1.** The experiment flow.

### 2.3. Specimens casting and curing

There were three types of specimens. The compressive specimens of concrete were prisms with the dimensions of $100 \times 100 \times 300$ mm. The compressive specimens of mortar were prisms with the dimensions of $70.7 \times 70.7 \times 210$ mm. All the tensile specimens were in the shape of dumbbell as shown in Fig. 3. The area of the cross section of the middle part is about $100 \times 100$ mm. An ITZ tensile specimen is shown in Fig. 4.

All the concrete were mixed and cast in accordance with the requirements of the Chinese Evaluation Standard for Concrete Strength "GBJ107-87" [8]. After demolding, the specimens were stored under standard moist curing conditions at 23 °C and 95% RH till testing. The parent concrete specimens were cured until the recycled concrete specimens also finished curing. This should give similar strength to the old white mortar in both parent concrete and recycled concrete due to the same curing period. All the specimens were tested after the recycled concrete was cured for 28 days.

### 2.4. Test loading

Physical properties of natural aggregates and recycled aggregates, including bulk density, apparent density, and water absorption capacity were tested with the method according to the Chinese Standard of Pebble and Crushed Stone for Building "GB14685-2001" [9]. Due to the different colors of the natural aggregates and the old hardened mortar, the manual separation was used to identify the old mortar from the recycled aggregates. The identified area fraction of old mortar was then approximated to the volume percentage of this phase in recycled concrete.

The compressive tests were performed by the electron universal test machine of CSS44500. The experimental setup is shown in Fig. 5a. Stroke control mode as used during the tests. The displacement rate of the tests was kept constant at 0.01 mm/min. The axial compression and the strain of the test specimens were automatically collected by a computer. The strain data were collected with two strain gauges set on two opposite sides of the specimens. Each specimen was preloaded to 30–40% of the estimated peak loading for three times before the actual loading was applied. With the above method, the stress–strain curve was obtained for each specimen. The strength and the peak strains were also recorded. The Young's modulus was calculated based on the slope of the stress–strain curves within the region of 10–30% of the strength.

The tensile tests were performed with the electron universal test machine of CSS44100. The specimens were glued to the surface of a thick steel board, and 4 bolts were used to connect this steel board with another steel board. A steel bar connecting the second steel board was then fastened with the clamp of the test machine to exert tension on the specimens. The experimental setup is shown in Fig. 5b. Preloading was also carried out similar to that of compressive test. The unevenness of the tensile stresses was decreased through adjusting the four screws between the two steel boards. During the test, four steel bars were used to connect the loading board to avoid brittle break. Strain gauges were used to attain the strains of concrete and also the four steel bars. The stresses on concrete were calculated from

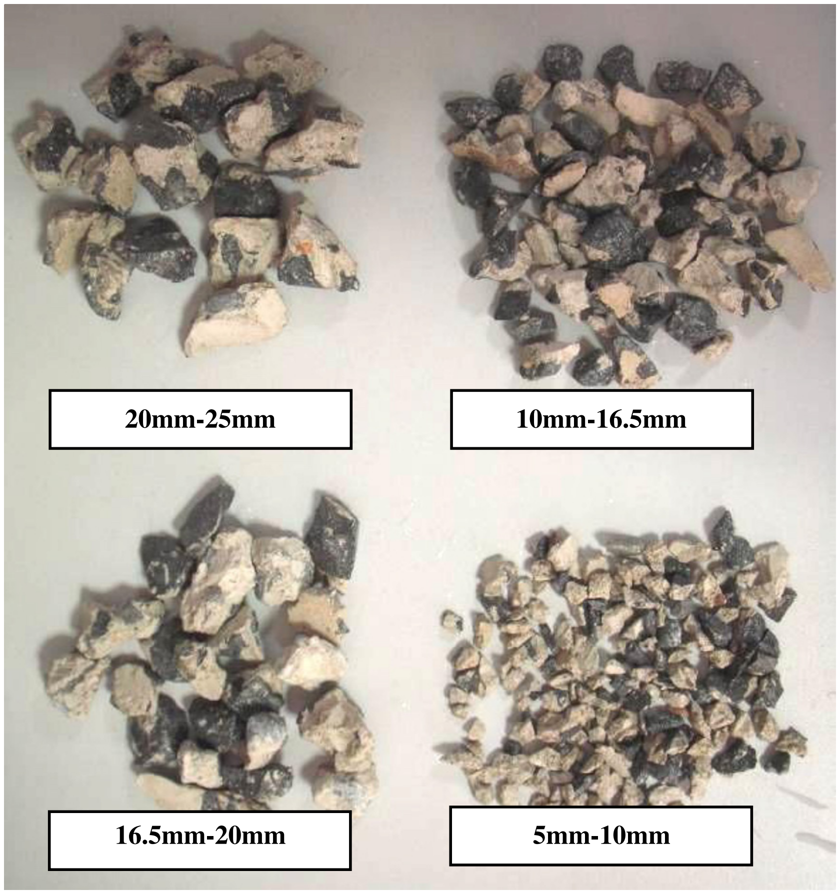


**Fig. 2.** Recycled aggregate.

the applied load minus the stresses in the four steel bars. The stresses in steel bars were calculated with the measured strains and the steel's Young's modulus. The tensile strength, peak strains and Young's modulus were also recorded in the stress–strain curves.

## 3. Results and discussions

### 3.1. Quantity and distribution of each phase

Figs. 6 and 7 show different colors of natural aggregates, old mortar and new mortar that used in the experiments of this study. It is easy to identify each phase so that the quantity of each phase was obtained by analyzing their area fractions in the cut section with area of 100 mm × 100 mm. The area fractions of each phase in concrete were then approximate to their corresponding volume percentages [10].

Fig. 6a shows an image of a cross section of parent concrete, and Fig. 6b shows the processed image of the same section. In both images, the dark color represents natural aggregates and the white color represents hardened mortar. From Fig. 6b, the number of pixels (NPs) was automatically obtained by software PHOTOSHOP. By counting the total pixels of each color, the area fractions of each phase were determined. Table 4 lists the NPs of each phase of three different cross sections of parent concrete C20. And it is easy to calculate the percentages of each phase.

For recycled concrete, an image of a cut sectional area and the corresponding processed image are shown in Fig. 7. Same as Fig. 6, the dark color is natural aggregates, the white color is old hardened mortar and the grey color is new hardened mortar. Area fractions of each phase were identified and calculated with exactly the same procedures as described for parent concrete. The numbers of pixels and area fractions of each phase of three cut sectional areas of recycled concrete RC20–20 are listed in Table 5. Both Tables 4 and 5 show that the area fractions of each phase obtained from three different samples have some variations. However, these variations are within an acceptable range.

### 3.2. Physical properties

The physical properties of recycled aggregate are listed in Table 6. And the properties of natural aggregate are also given in Table 6 for comparison purposes. From the table, it was observed that the densities of both recycled aggregates (RA) made from two different parent concrete are lower than the NA density, while both RAs have much higher water absorption than that of NA. This is due to the higher porosity in RA. The densities of parent concrete and their mortar matrix are shown in Fig. 8, while the densities of recycled concretes and their mortar matrix are shown in Fig. 9. From these figures, it was found that, in this study, the concrete and

**Table 3**
The gradation of the recycled coarse aggregate.

| Size of test sieve (mm) | 5 | 10 | 16.5 | 20 | 25 |
|---|---|---|---|---|---|
| Percentage passing of RA20 (%) | 0 | 30.9 | 64.2 | 82.9 | 100 |
| Percentage passing of RA30 (%) | 0 | 33.1 | 65.3 | 83.5 | 100 |

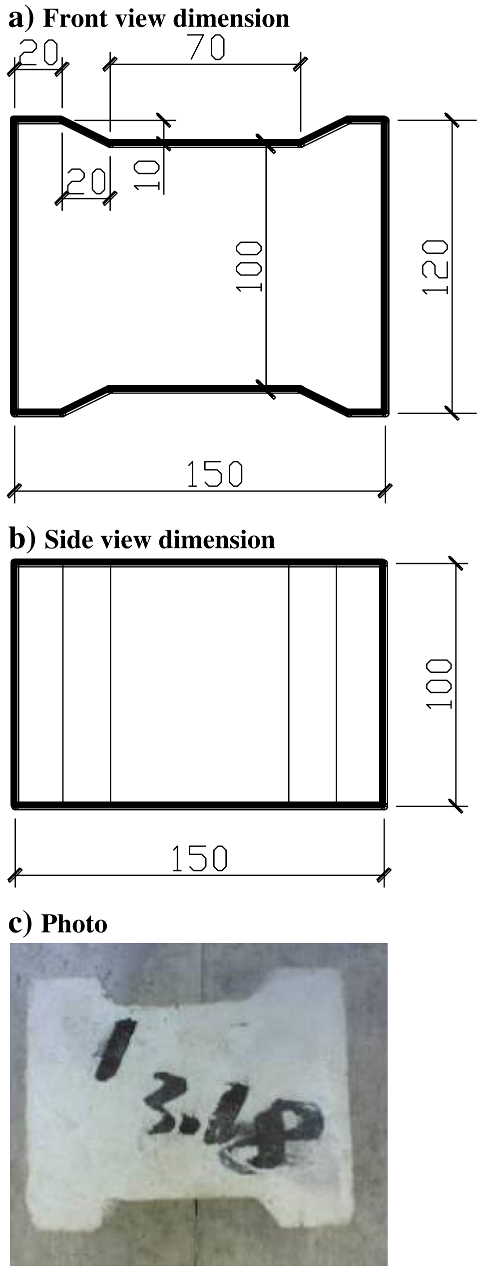


**Fig. 3.** Tensile specimen.

mortar with higher strength have higher density. In addition, the white mortar (old mortar, OM20 and OM30) has a lower density than the grey mortar (new mortar, NM20 and NM30). By comparing Figs. 8 and 9, it was also noticed that with similar strength, the recycled concrete always has a lower density than the parent concrete. For example, the density of RC20–20 is 2321 kg/m$^3$, while the density of C20 is 2389 kg/m$^3$. This is due to the extra old hardened mortar in recycled concrete.

### *3.3. Mechanical properties of parent concrete and old mortar*

The mechanical properties including the compressive and tensile strengths, the Young's modulus, and the peak strain of parent concrete were obtained from the tests described in Section 2.4. Three specimens of each concrete or mortar were prepared for both compressive and tensile tests. The values of each mechanical property are displayed in Figs. 10–12.

From Fig. 10, it was found that the parent concrete has a lower compressive strength and a higher tensile strength than the corresponding mortar. For compressive strength, the rough surface together with the irregular shape of the coarse aggregates will cause stress concentration, which may introduce cracking along the surface of coarse aggregates. Researchers also found that compared to the ITZs around sand, ITZs around coarse aggregates normally have a much higher chance to contain flaws and the flaw sizes are normally bigger, which will greatly reduce the compressive strength. However, these cracks in ITZs absorb energy during the cracking process, which enhance the ductility of the concrete. For the tensile strength, it was observed during each test that the fracture planes of concrete were always more uneven than those of mortars and the fracture planes were always located along the ITZ. Compared to a mortar sample, the length and the unevenness of the fracture plane together with the interlock between coarse aggregates enhanced the tensile strength of concrete.

Fig. 11 shows the variations of the Young's modulus. It was found that, for each mixture, the compressive Young's modulus of parent concrete is higher than that of tensile one. Some other researchers got the similar results [11]. This may attribute to the contribution from the stiffness of natural aggregates. However, the natural aggregates hardly have any contribution to the tensile Young's modulus because the tensile tests were governed by the fractures along ITZ. For mortar, the compressive Young's modulus is approximately equal to the tensile one.

Fig. 12 shows the peak strains of all the specimens. It can be seen that the compressive peak strain of concrete is about 0.002, while the compressive peak strain of mortar is about 0.004, which is similar as reported in Ref. [12]. The tensile peak strain of concrete and mortar are almost the same, which approximately equal 0.0001.

### *3.4. Mechanical properties of recycled concrete and new mortar*

The testing results of recycled concrete are shown in Figs. 13–15. During the experiments, some samples were broken due to some unexpected reasons. So, only two experimental data were reported for some mixtures.

By comparing Fig. 13 with Fig. 10, it was found that the recycled concrete has higher strength than parent concrete. This is attributed to the grey cement which has a higher strength than white cement with the same water-to-cement ratio. From Fig. 13, it was also found that the strength of RC increases with the increasing strength of the corresponding new hardened mortar. For example, when the new hardened mortar changes from NM20 to NM30, the compressive strength is increased by 44%. The compressive strength of RC20–30 is 31% higher than that of RC20–20; and the compressive strength of RC30–30 is 44% higher than that of RC30–20. Similar increasing rates can be observed for tensile strength.

When the recycled aggregate changes from RA20 to RA30, that is the old hardened mortar changes from OM20 to OM30 (the compressive strength is increased by 54%), the compressive strength of recycled concrete RC30–20 is 5.7% higher than RC20–20; and the compressive strength of RC30–30 is 16% higher than RC30–20. This means compared with the influence of new hardened mortar, the old hardened mortar does not influence the strength of recycled concrete significantly.

From Fig. 14, it can be observed that the new hardened mortar has a significant influence on the Young's modulus of recycled concrete. For example, both the compressive and tensile moduli of RC20–30 are higher than those of RC20–20. However, the modulus of RC20–20 and those of RC30–20 have very similar values; this is also true for RC20–30 and RC30–30. This means the old mortar has very minor effects on the modulus of recycled concrete. This phenomenon is due to the quantity and distribution of old mortar. From the image analysis of the

**Fig. 4.** ITZ simulation tensile specimen.

cross sections of the recycled concrete, new hardened mortar takes about 52% of the total volume, while the old hardened mortar takes only about 23%. The larger volume percentage of the new hardened mortar makes it a dominant factor to the Young's modulus of the recycled concrete.

From Fig. 15, it can be seen that the average of the peak strains of four recycled concrete is 0.00222 and the average tensile peak strains of recycled concrete is about 0.0001. The compressive peak strains are higher than those of parent concrete that used in this study.

### 3.5. Tensile strength of ITZ

For each tension test, the broken cross sections were observed after the test. It was found that majority of cracks appeared in new

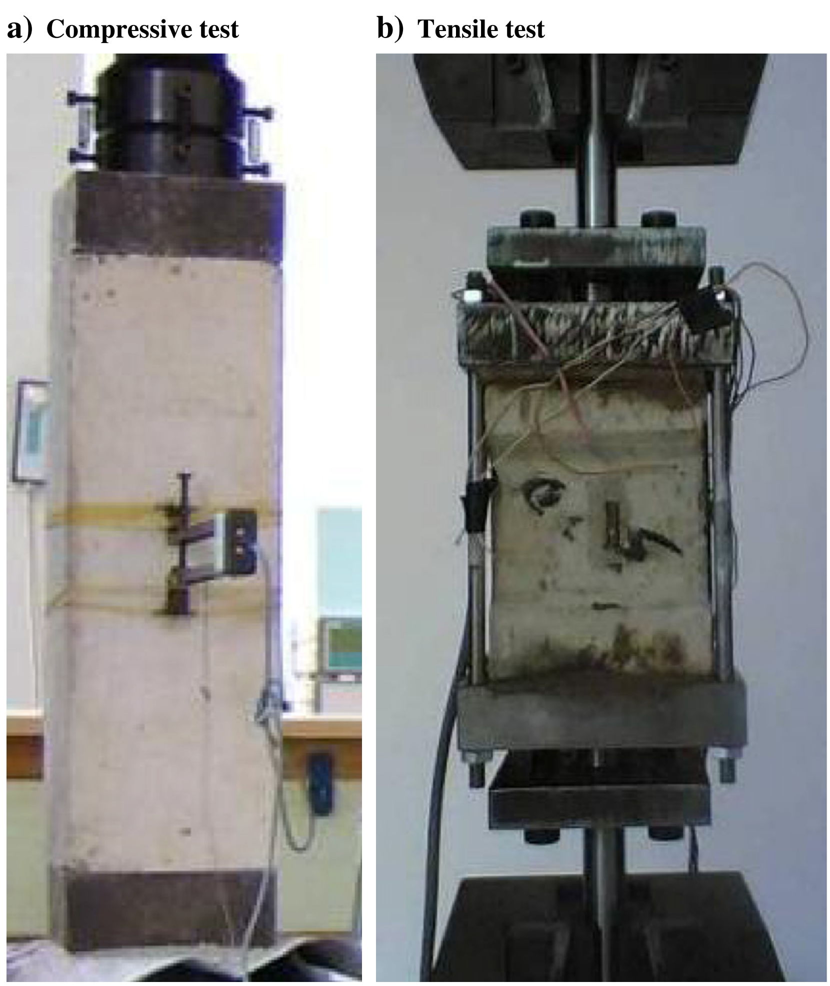


**Fig. 5.** The test method.

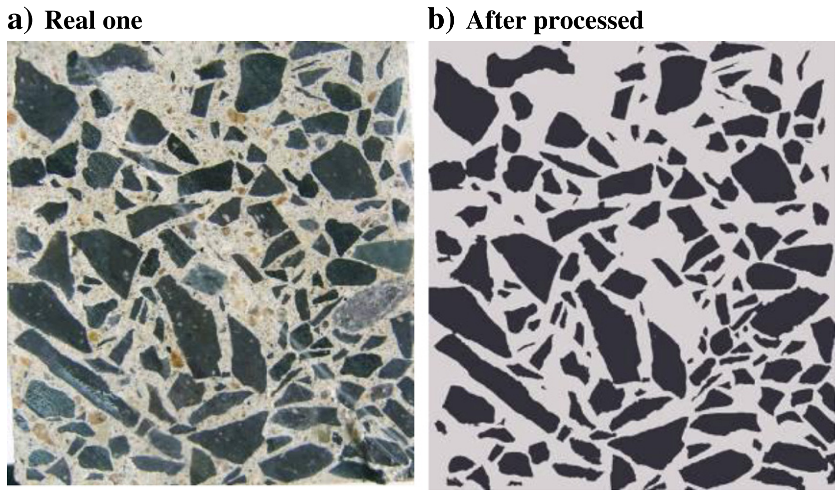


**Fig. 6.** Cut section of parent concrete.

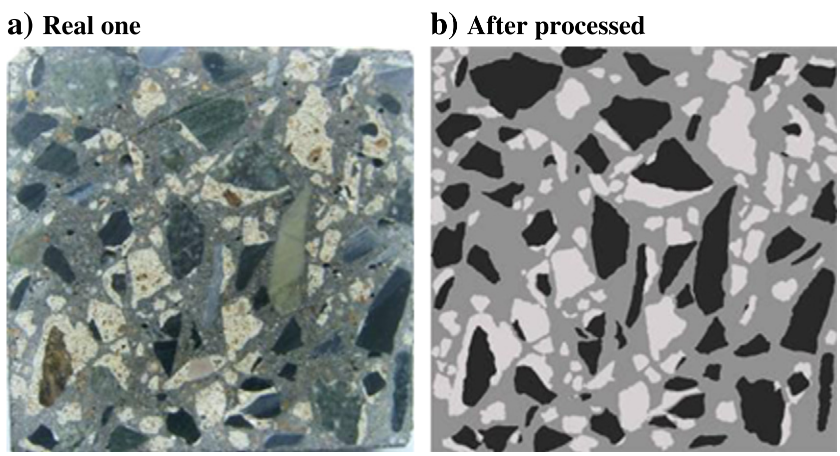


**Fig. 7.** Cut section of recycled concrete.

**Table 4**
The number pixels of each phases in parent concrete.

| | Total NPs | NA | | OM | |
|---|---|---|---|---|---|
| | | NPs | % | NPs | % |
| No.1 | 152,375 | 69,089 | 45.3 | 83286 | 54.7 |
| No.2 | 140,571 | 57,685 | 41.0 | 82886 | 59.0 |
| No.3 | 126,763 | 60,611 | 47.8 | 66152 | 52.2 |
| Avg | | | 44.7 | | 55.3 |

**Table 5**
The number of pixels of each phase in recycled concrete RC20–20.

| | Total NPs | NA | | OM | | NM | |
|---|---|---|---|---|---|---|---|
| | | NPs | % | NPs | % | NPs | % |
| 1 | 151,456 | 40,613 | 26.8 | 34,213 | 22.6 | 76,630 | 50.6 |
| 2 | 151,305 | 36,160 | 23.9 | 34,922 | 23.1 | 80,223 | 53.0 |
| 3 | 152,330 | 35,744 | 23.5 | 35,197 | 23.1 | 81,389 | 53.4 |
| AVG | | | 24.7 | | 22.9 | | 52.3 |

mortar and old mortar (point 1 in Fig. 16). Some cracks go through the ITZ formed by natural aggregates and old mortar (point 2 in Fig. 16). Cracks going through the ITZ formed by natural aggregates and new

**Table 6**
Physical properties of natural aggregate and recycled aggregate.

| | NA | RA20 | RA30 |
|---|---|---|---|
| Bulk density(kg/m$^3$) | 1250 | 1165 | 1195 |
| Apparent density (kg/m$^3$) | 2790 | 2415 | 2429 |
| Water absorption (%) | 0.4 | 6.90 | 5.26 |
| Percentage of old mortar (%) | 0 | 42.22 | 46.51 |

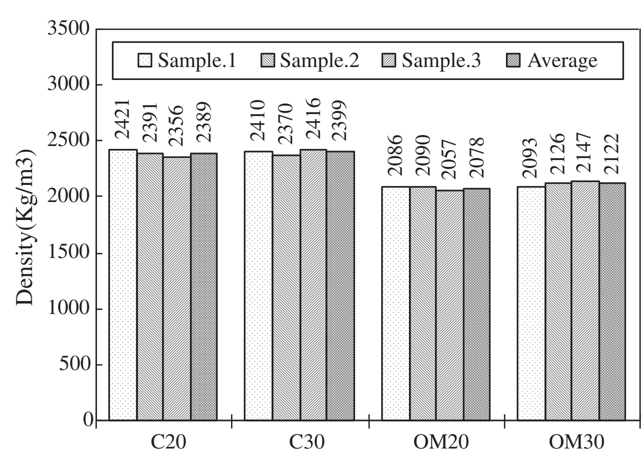


**Fig. 8.** Density of parent concrete and old mortar.

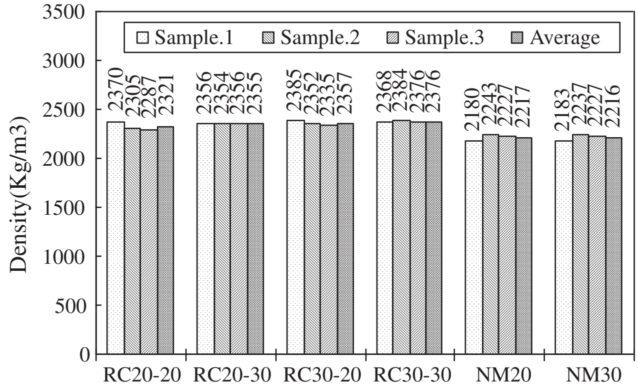


**Fig. 9.** Density of RC and new mortar.

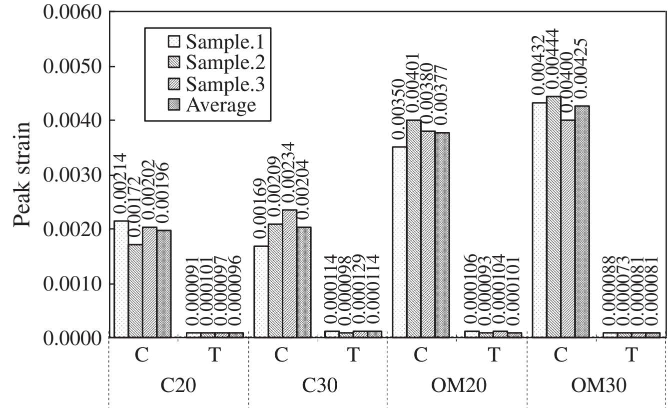


**Fig. 12.** Peak strain of parent concrete and old mortar.

mortar were also found (point 3 in Fig. 16), and some cracks were found to go through natural aggregates as shown in Fig. 16 (point 4). However, very few cracks were found to go through the ITZ formed by old mortar and new mortar. This indicates that the new mortar has good bonding with the old mortar in a recycled concrete.

The tensile strength of ITZ was measured with the method described in Section 2.1. The ITZ strength was found to be 1.021 MPa and 1.321 MPa for specimens made of NM20 and NM30, respectively. The ITZ strength is about 60% of the tensile strength of new mortar that was used.

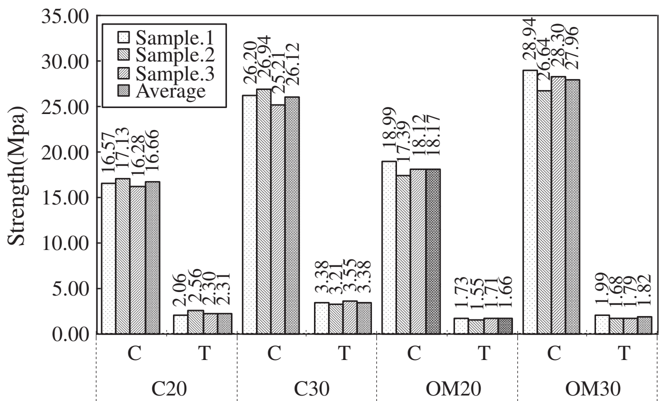


**Fig. 10.** Strength of parent concrete and old mortar.

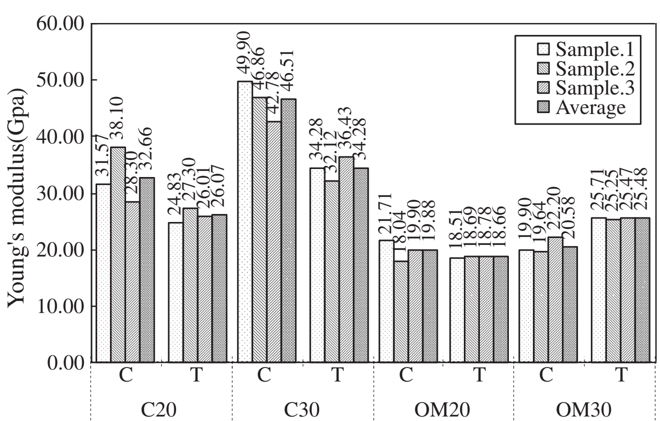


**Fig. 11.** Young's modulus of parent concrete and old mortar.

## 4. Conclusions and suggestions

The experimental results have revealed the failure process and mechanism of recycled concrete under both tensile and compressive loading. From this investigation, the following conclusions are drawn:

1) Compared with old hardened mortar, new hardened mortar has more significant influences on both the strength and Young's modulus of recycled concrete.
2) The cracks are most likely to appear first within ITZs between natural aggregates and hardened mortar including new and old ones. Compared with new mortar, the old mortar in recycled concrete has a higher tendency to crack.
3) Due to the large volume content of hardened mortar (both old and new), some of the mechanical properties of recycled concrete are similar to those of mortar. So compared to parent concrete, recycled concrete with similar mix proportions normally has a lower elastic modulus, a lower strength, and a higher peak strain.
4) This research was undertaken in the laboratory. It should be mentioned that recycled aggregates on a construction site are different in the aspects of attached hardened mortar and surface conditions such as clay. Some further investigations need to be performed to study the influences of the ITZ quality on the distinctness of the mechanical properties of recycled concrete.

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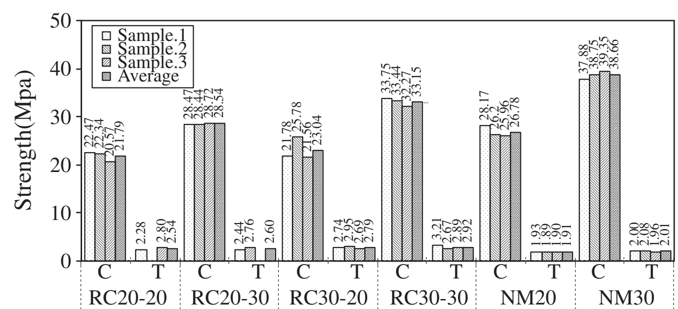


**Fig. 13.** Strength of RC and new mortar.

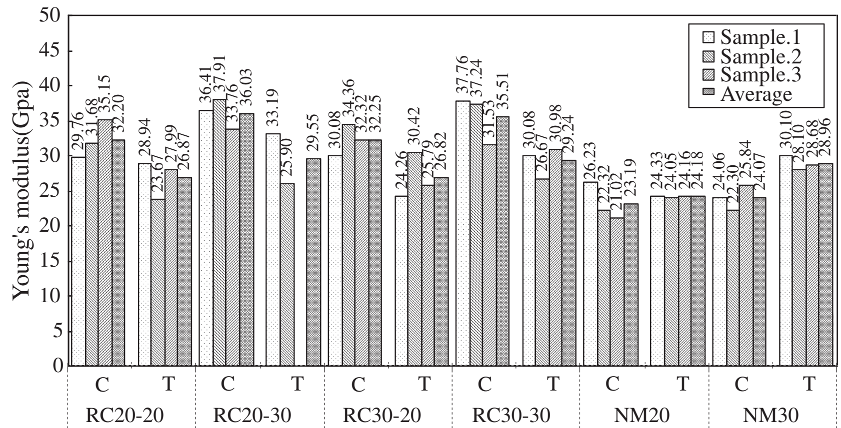


**Fig. 14.** Young's modulus of RC and new mortar.

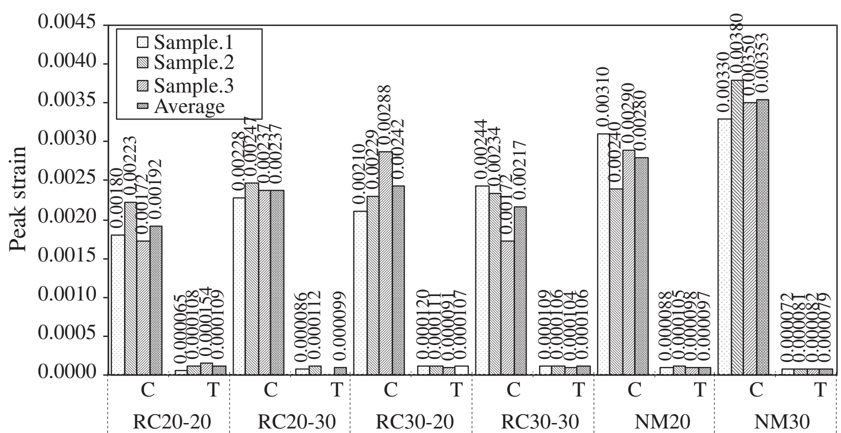


**Fig. 15.** Peak strain of RC and new mortar.

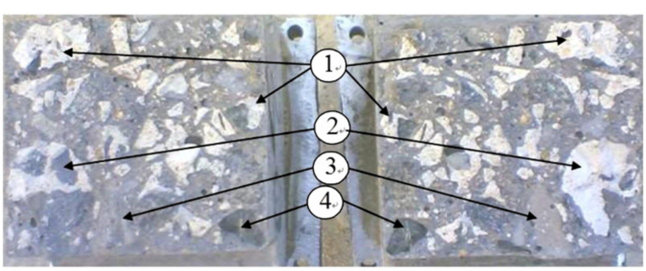


**Fig. 16.** Tensile break section of recycled concrete.

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