Study on conversion relationships of compressive strength indexes for recycled lightweight aggregate concrete

Xiang-gang Zhang¹,²,³, Jian-hui Yang¹,²,⁴ and Xiao-mei Kuang²

¹ Henan Polytechnic University, Henan Province Engineering Laboratory of Eco-architecture and the Built Environment, Jiaozuo 454000, China;
² Henan Polytechnic University, School of Civil Engineering, Jiaozuo 454000, China;
³ Guangxi Key Lab of Road structure and materials, Nanning 530000, China.

E-mail: xgzhang@hpu.edu.cn

Abstract: In order to study cube compressive strength and axial compressive strength of recycled lightweight aggregate concrete (RLAC), and conversion relationship between the two, with the replacement rate of recycled lightweight coarse aggregate as change parameters, 15 standard cube test specimens and 15 standard prism test specimens were produced to carry out the test. Then compressive strength of test specimens were measured, and the law of different replacement rate of recycled lightweight coarse aggregate influencing compressive strength of RLAC was analyzed, as the method of statistical regression adopted, the conversion relationships between of cube compressive strength and axial compressive strength of RLAC was obtained. It is shown that compressive strength of RLAC are lower than compressive strength of ordinary concrete; and that compressive strength of RLAC gradually decreases as replacement rate of recycled lightweight coarse aggregate increases; as well as, the conversion relationship between axial compressive strength and cube compressive strength of RLAC is different from ordinary concrete; based on the experimental data, conversion relationship formula between compressive strength indexes of RLAC was established. It is suggested that the replacement rate of recycled lightweight aggregate should be controlled within 25%.

1. Introduction

Construction waste is increasing in China with the rapid development of urbanization in recent years, how to deal with the construction waste has become a difficult problem for scientific research workers [1,2]. According to the statistics [3], at present, construction waste has reached 30%~40% of the city rubbish, among which 50%~60% is the waste concrete in China. It will seriously pollute the environment if these constructions aren’t utilized scientifically and effectively. Through those steps of classifying, crushing, washing and drying, the recycling of construction waste will be mixed to be the recycled aggregate formation according to the design of the mixed proportion and gradation. Sand and other natural coarse aggregate were replaced partially or even totally by the recycling of construction waste, and it can be configured to be recycled concrete after adding water and cement [4-6]. Recycling those wastes of concrete can decrease the consumption of natural aggregate in the construction industry and alleviate the pressure of the increasing lack of natural aggregate, meanwhile, the economic and social benefits are obvious. Above all, it has more important practical significance for protecting ecological environment [7, 8].

At present, studying on conversion relationships between compression strength indexes of recycled aggregate concrete is in a preliminary stage. Among them, Xiao Jianzhuang et al [9] studied...
comprehensively on relationships between strength indexes of recycled aggregate concrete, tested the strength of the specimens, and initially obtained the conversion relationships between cube compressive strength of recycled concrete and other strength indexes through statistical regression of experimental data. Experiments showed that recycled concrete was similar with ordinary concrete in flexural strength, but the conversion relationship between the strength indexes of recycled concrete and ordinary concrete is different. Chai Yuanyuan et al. [10] studied on conversion relationships between basic mechanical properties indexes of recycled aggregate concrete and proposed the conversion relationships of some basic mechanical properties indexes of recycled concrete. Lu Shengwu et al. [11] studied on the compressive strength of recycled concrete using waste ceramic as fine aggregate, it is shown that the conversion relationship between the compressive strength and the tensile strength of recycled concrete was different from ordinary concrete. A formula on the conversion by compressive strength to tensile strength of recycled concrete was established.

In the past studies, it has been done mostly on recycled concrete derived from ordinary waste concrete, but little research on new recycled concrete from waste lightweight aggregate concrete, and no relevant literature has been found yet. It is very necessary to study the advantages of natural aggregate and waste lightweight aggregate concrete in a certain proportion, which can reduce the weight of the structure, save the natural aggregate and so on.

In this paper, the compressive strength of RLAC of 30 test specimens were carried out, and analyzed law that the effect of replacement rate of recycled lightweight aggregate on the compressive strength of RLAC. The conversion relationship between the axial compressive strength and the cube compressive strength was established, and can provide a reference for the research of RLAC.

2. Experiment

2.1. Raw materials

Natural coarse aggregate adopted continuous gradation of gravel, as shown in Figure 1 (a); The recycled lightweight aggregate (design strength grade LC20) was prepared by crushing, screening, washing and drying the lightweight concrete specimens after being tested at a structure hall of university in Henan Province, as shown in Figure 1 (b). The sand gradation was medium; ordinary tap water was used as mixing water; the cement was PO42.5 produced by a Jiaozuo cement limited. Basic physical properties of the coarse aggregate and recycled coarse aggregate are shown in Table 1. It can be concluded that the water absorption rate of the recycled lightweight aggregate is much larger than that the natural coarse aggregate, which can reach 9.46%. The reason is that the rough surface of recycled coarse aggregate, and more internal voids.

![Figure 1. Coarse aggregate](image)

(a) Natural coarse aggregate  
(b) Recycled coarse lightweight aggregate

| Table 1. The basic physical property indexes of coarse aggregate |
|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Aggregate Category | Grain size/mm  | Bulk density (kg/m³) | Apparent density (kg/m³) | Water absorption rate/% | Voidage/% |
| Natural coarse aggregate | 5.00-31.50 | 1481.00 | 2500.00 | 0.62 | 40.76 |
| Recycled lightweight coarse aggregate | 5.00-31.50 | 776.00 | 1389.00 | 9.46 | 44.13 |
2.2. Mix proportions

In this experiment, 5 types (0%, 25%, 50%, 75%, 100%) of replacement rate were designed, the replacement rate was designed according to the mass percentage of the recycled lightweight aggregate to the total coarse aggregate. The replacement rate of 0% of the test specimen as a natural test specimen, and the remaining test specimens as the contrast test specimens. 15 cube test specimens and 15 prism test specimens were produced, in each group of replacement rate was 3 cube specimens and 3 prism specimens. Water absorption rate was tested according to the 《Light aggregate and its test method》 (GB/T17431.2-2010), considering the rough surface and higher water absorption rate of recycled coarse aggregate, therefore, additional water was added as compensation, and the amount of additional water was obtained by the product of the recycled light coarse aggregate and its water absorption rate. Under the different replacement rate, the mixed proportion of quality of LC20 RLAC is shown in Table 2.

| Replacement rate | Cement /kg | Natural coarse aggregate/kg | Recycled lightweight coarse aggregate/kg | Sand /kg | Net duty of water/kg | Additional water/kg | Effective water to binder ratio |
|------------------|------------|-----------------------------|----------------------------------------|----------|-----------------------|---------------------|-----------------------------|
| 0%               | 440.00     | 1066.32                     | 0.00                                   | 634.08   | 208.00                | 0.00                | 0.47                        |
| 25%              | 440.00     | 799.74                      | 139.68                                 | 634.08   | 208.00                | 13.21               | 0.47                        |
| 50%              | 440.00     | 533.16                      | 279.36                                 | 634.08   | 208.00                | 26.43               | 0.47                        |
| 75%              | 440.00     | 266.58                      | 419.04                                 | 634.08   | 208.00                | 39.64               | 0.47                        |
| 100%             | 440.00     | 0.00                        | 558.72                                 | 634.08   | 208.00                | 52.85               | 0.47                        |

Note: Effective water-cement ratio is the ratio of net duty of water to cement quality.

2.3. Preparation of specimens and loading

The size of the test specimens was designed to be 150mm×150mm×150mm standard cube test specimen and 150mm×150mm×300mm standard prism specimen. Standard size of steel mould were used for the test, and the recycled concrete was molded according to the 《Standard test method for the performance of ordinary concrete》 (GB/T50080-2002). The moulds were removed from the forming specimens after 24 h in the structure hall, to be the standard curing 28d after loading, measured its compressive strength.

Figure 2. Loading setup

This test was carried out according to the loading method of the 《Ordinary concrete mechanical property test method》 (GB50081-2002), the loading setup as shown in Figure 2 adopted a SYE-2000 pressure testing machine and the maximum range was 2000kN. The loading rate of the test specimens was kept constant 9kN/s in this experiment.
3. Test results and influence factors

3.1. Dry apparent density

According to the study [12], the dry apparent density has a direct relationship between the compressive strength of test specimen and replacement rate. The three groups of cube test specimens had produced under the different replacement rate, and its size is 100 mm × 100 mm × 100 mm. After the standard curing, test specimens were dried to constant weight by using the model of SY101-2 electric blast oven in the range of 105°C, and then the dry apparent density of RLAC with different replacement rates was calculated after measuring its quality as shown in Table 3.

| Replacement rate | 0%  | 25% | 50% | 75% | 100% |
|------------------|-----|-----|-----|-----|------|
| Dry appearance density/(kg/m³) | 2353 | 2200 | 2085 | 1839 | 1705 |

It can be seen from Table 3 that the dry apparent density of RLAC is lower than that of ordinary concrete, and the dry apparent density of RLAC decreases with the increasing of replacement rate. The magnitude of the reduction (this is the difference between the latter and the former accounting for the former) were 6.50%, 5.23%, 11.80% and 7.29% respectively. With the gradual increase of the replacement rate, the dry apparent density of the specimen have a linear relationship with the replacement rate, as shown in Figure 3.

According to the data in Table 3, the least square method is used to fit the relationship between the apparent density and the replacement rate, as shown in Figure 3.

Obviously, the mathematical expression of the relationship between the dry apparent density and the replacement rate curve is

\[ y = 2367.8 - 662.8x \]  

Where \( y \) is the drying apparent density, \( x \) is the replacement rate of recycled lightweight concrete, formula (1) has fitting precision of 0.98.

3.2. Process and pattern of failure

The failure process of RLAC test specimen and ordinary concrete test specimen is approximately similar. At the initial stage of loading, there was no significantly change in the surface of the test
specimens; the internal stress of test specimens increased with the increase of compression loading; as the load continues to increase, specimen’s surface began to appear some smaller cracks and micro-cracks with the generating sound of faint crackling, and gradually expand, through; test specimens were failure when the load increased to the ultimate load; the failure cracks of all test specimens were basically along the vertical direction, which was inconsistent with the inclination angle of the crack of the ordinary recycled concrete[13]. But the destructive pattern of RLAC was different from ordinary concrete, the features of porous and brittle texture of recycled lightweight aggregate made the cube specimens damage along the direction parallel to the crack, and was different from the damage of the inverted cone of ordinary concrete. The failure of the prism first appeared from the surface of micro-cracks, and then began to expand and through, the test specimens were damaged due to a large area of the occurrence of massive spalling in the end. The failure patterns of some cube test specimens and prism test specimens are shown in Figure 4(a), (b), (c), (d), (e) and (f), by observing the failure of the test specimens, the damage area of RLAC is found mainly in the aggregate interface and the recycled light aggregate itself.

3.3. Compressive strength
The ultimate load of all the test specimens was measured, and test specimens were known actual bearing area. Methods provided according to the《Mechanical properties of ordinary concrete test method》(GB50081-2002), the cube compressive strength and axial compressive strength of RLAC were calculated, as shown in Table 4.

| Replacement rate | $f_{cu}$/MPa | $f_c$/MPa | $f_c/f_{cu}$ |
|------------------|-------------|-----------|-------------|
| 0%               | 37.62       | 25.55     | 0.68        |
| 25%              | 31.82       | 24.76     | 0.78        |
| 50%              | 27.72       | 24.53     | 0.88        |
| 75%              | 26.68       | 22.54     | 0.84        |
| 100%             | 20.57       | 21.30     | 1.04        |

Note: $f_{cu}$ is the cube compressive strength; $f_c$ is the axial compressive strength.

From Table 4, the cube compressive strength and axial compressive strength of RLAC meet the design strength, and the ratio of axial compressive strength to cube compressive strength of RLAC is higher than the ordinary concrete. When the replacement rate of recycled lightweight aggregate is 100%, the compressive strength of the cube test specimens are lower than the axial compressive strength, this is because the coarse aggregate of RLAC was composed entirely of the regenerated lightweight aggregate at this time; it is the lowest that the dry apparent density of RLAC with sparse and brittle materials, and then the restraining range of the bearing surface of the test specimen is reduced, which make the failure pattern of the cube specimens closes to the prism specimens (Figure 4); it is limited that the increase of cube compressive strength, coupled with the dispersion of the larger concrete itself, and then led to the occurrence of the phenomenon.

Obvious, the law of the compressive strength and the replacement rate is shown in Figure 5 and Figure6.

It can be seen from Figure 5 that the cube compressive strength of RLAC is linear with the replacement rate of recycled lightweight aggregate. The measured compressive values were fitted to the expression by using the principle of least square method:

$$y = ax + b$$  \hspace{1cm} (2)

Where the values of a and b are 15.70 and 36.73 respectively, and the fitting precision is 0.95.

It can be seen from Figure 6 that the axial compressive strength of RLAC has a linear relationship with the replacement rate of recycled lightweight aggregate. The least square method is used to fit the expression:

$$y = ax + b$$  \hspace{1cm} (3)
Where the values of a and b are respectively -4.29 and 25.88, and the fitting precision is 0.91.

Figures 5 and 6. Relation curve between cube and axial compressive strength and replacement rate

3.4. Influence factor analysis

Under different replacement rates, the cube specimens of recycled lightweight aggregate and the axial compressive strength are shown in Figure 7 and Figure 8.

Figures 7 and 8. Cube and axial compressive strength under different replacement rate

From Figure 7 and 8 show that the compressive strength of RLAC is lower than the compressive strength of ordinary concrete. With the replacement rate increasing, the cube compressive strength of RLAC and the axial compressive strength is decreased, which is due to the interior of recycled lightweight aggregate accumulates more cracks and micro cracks. The initial damage increase gradually with the increase of replacement rate, and the strength decreases gradually at the macro level. With the increase of replacement rate, the reduction of the compressive strength of the cube specimen is 15.42%, 12.88%, 3.75%, 22.90% respectively, the magnitude of decrease of axial compressive strength is 3.09%, 0.93%, 8.11%, 5.50% respectively. Thus, only when the replacement rate of recycled lightweight aggregate from 50% to 75%, the change of cube compressive strength is not obvious; only when the replacement rate of recycled lightweight aggregate from 25% to 50%, the change of axial compressive strength is not obvious; When the replacement rate of the recycled lightweight aggregate is changed in turn, the decrease of the cube and axial compressive strength is obvious. But when the replacement rate from 0% to 25% to 50%, the magnitude of change of axial compressive strength is far less than 5%. In order to facilitate the popularization and application of RLAC, it is suggested that the replacement rate of recycled light aggregate should be controlled within 25% in the mix proportion of recycled lightweight aggregate.
3.5. The conversion relationship of compressive strength

For ordinary concrete, the conversion relationship[14] between the axial compressive strength and the cube compressive strength is

\[ \frac{f_c}{f_{cu}} = 0.76 \]  

(4)

For the RLAC, due to the mechanical properties of recycled lightweight aggregate and ordinary aggregate are very different. The conversion relationship of compressive strength of ordinary concrete is no longer suitable for RLAC. As can be seen from Table 4 shows that the ratio of the axial compressive strength to cube compressive strength of RLAC is closely related to the replacement rate of recycled lightweight aggregate. In general, with the increase of the replacement rate, the ratio of axial compressive strength to cube compressive strength increases gradually. Figure 9 shows the changeable law of the ratio of axial compressive strength and cube compressive strength to the replacement rate of recycled lightweight aggregate through measured data. Based on this changeable law, the following mathematical model is proposed:

\[
y = \begin{cases} 
    ax + b & 0 \leq x \leq 0.5 \\
    x + \frac{1}{cx + d} & 0.5 < x \leq 1 
\end{cases}
\]  

(5)

Where \( y = \frac{f_c}{f_{cu}} \), \( x \) is the replacement rate of recycled lightweight aggregate.

After measuring data, the ratio of the axial compressive strength to the cube compressive strength of RLAC is shown in Figure 9, which is fitted by using the least square method.

The control parameters \( a \) and \( b \) is 0.40 and 0.68 respectively in the upper half of the fitting curve, the fitting accuracy is 1.00, the lower half of the control parameters \( c \) and \( d \) is 36.5 and -15.6 respectively, and the fitting precision is 0.99. The relationship between the axial compressive strength and the cube compressive strength of RLAC is obtained by the method of statistical regression:

\[
f_c = \begin{cases} 
    (0.4x + 0.68)f_{cu} & 0 \leq x \leq 0.5 \\
    (x + \frac{1}{36.5x - 15.6})f_{cu} & 0.5 < x \leq 1 
\end{cases}
\]  

(6)

It can be seen in the Table 5 that the comparison between the calculated values and the measured values by using equation (6).

| Replacement rate | Measured value | Calculated value | The ratio of calculated value to measured value |
|------------------|----------------|-----------------|-----------------------------------------------|
| 0                | 37.62          | 25.55           | 1.00                                          |
| 25%              | 31.82          | 24.76           | 1.00                                          |
| 50%              | 27.72          | 24.53           | 0.99                                          |
| 75%              | 26.68          | 22.54           | 0.99                                          |
| 100%             | 20.57          | 21.30           | 1.01                                          |

It can be concluded from Table 5 that the ratio of measured value to calculated values is 1.00 about the \( f_c \), the variance is 0.00 and the coefficient of variation is 0.01, the calculated values by using equation (6) is in good agreement with the measured values.
4. Conclusions

- The ratio of axial compressive strength to cube compressive strength of RLAC is higher than the ordinary concrete;
- With the gradual increase of the replacement rate of recycled lightweight aggregate, the compressive strength of RLAC cube and axial are gradually decrease, the regularity is more obvious, and the strength is lower than the ordinary concrete;
- The conversion formula of compressive strength of ordinary concrete is not suitable for RLAC any more. Based on the measured data, it can establish the conversion relationships between compressive strength indexes of RLAC.
- In order to facilitate the popularization and application of RLAC, it is suggested that the replacement rate of recycled light aggregate should be controlled within 25% in the mix proportion of recycled lightweight aggregate.

Acknowledgments
The authors would like to thank 2017 Science and Technology Research Projects of Henan Province, 2016 Science and Technology Project of Prevention and Control of the Key Technology on Safety Production Major Accident (henan-0006-2016AQ), 2015 Jiaozuo Science and Technology Plan Project, Key Scientific Research Project of Colleges and Universities in Henan province (15A560008), Open Topic of Guangxi Key Lab of Road structure and materials(2015gxjgclks-004), for their generous support to the research projects.

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