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A Statistical Study on the Compressive Strength of Recycled Aggregate Concrete

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In order to explore the effect of RCA on the compressive strength of concrete, two RCAs from different sources are utilized to take experiments in this study. Four groups of concrete, including three RACs incorporated with various RCAs and another one made with natural aggregate (i.e. normal aggregate concrete (NAC)) are tested under an identical laboratory condition. The influence of RCA on the statistical parameters of the compressive strength, including the mean value, the standard deviation and the coefficient of variation are examined in detail. In addition, the fitted normal distribution modelto is used to describe the probability distribution characteristics of the compressive strength of the RACs, and the Monte-Carlo simulation technique is applied to verify the suitability of the normal distribution model for the probability distribution of the compressive strength of RAC. At last, it is summed up that the RCA does not have a significant effect on the variation and probability distribution of the compressive strength of concrete.

1. Introduction

Recycled aggregate concrete (RAC), was introduced into engineering practice many years ago. The application of RAC is beneficial for solving the increased waste storage problems, for reusing the large amount of waste concrete form the demolition of old concrete structures, and also for protecting the limited natural aggregate sources. Numerous studies covering the processing of the demolished rubble, the mix design, the material and structural behavior, and the economic and sustainability aspects of RAC have been carried out (Xiao et al., 2006). These findings have been summarized in some review papers and reports.

Since 1900s, due to the accelerated urbanization, numerous researchers in China have devoted themselves to the research and applications of RAC in practice. The most important achievements obtained in China in the past years on this topic have been extensively reviewed. It is revealed from the previous studies in China and other countries that RAC exhibits generally lower mechanical properties in comparison to normal aggregate concrete (NAC)(i.e. concrete produced with natural aggregates) (Li et al., 2006). However, until now there is no one test result indicating that RAC is not suitable for use in engineering practice. In the recent years, Significant studies have been carried out on the stiffness, deformation, strength, and ductility of structural components and structures made of RAC. A review of existing work on the structural behavior of RAC has recently been given. It is found that the cracking patterns and failure of RAC structural elements and structures are generally similar to that of NAC structures.

Although tremendous advances in understanding the material and structural behavior of RAC, there still exist some significant barriers in the practical application of RAC up to now. These barriers include the lack of appropriately located recycling facilities, the absence of appropriate technology, the lack of public awareness and government support, and the lack of proper standards, as pointed out (Hendriks, 1985). In addition, too little knowledge about the safety of structures made of RAC is another very significant barrier. It is often assumed that the coefficient of variation of the compressive strength of RAC increases in comparison to NAC, owing to the larger scatter in the quality and the composition of demolished concretes in practice (Rao et al., 2007). The increased scattering of the compressive strength of RAC reduces the safety of structural components and structures made of this material. This decreased structural safety obviously introduces additional worry when RAC is used in engineering practice. Therefore, the safety of structural elements and

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structures made of RAC should be carefully studied before this material can be used in practice with sufficient confidence.

The statistical characteristics of the compressive strength of concrete are of great importance for the reliable design and safety assessment of concrete structural elements and structures. For RAC, the use of RCA might increase the variations or uncertainties in the strength properties of such concrete due to the impurities introduced when producing RCA from waste concretes. Keeping this in view, the objective of the present work is to investigate the effect of RCA on the variations in the compressive strength of concrete (Xiao et al., 2005). Two RCAs from different sources were employed in this study. The effect of the RCA on the statistical parameters of the compressive strength, such as mean value, standard deviation, and coefficient of variation as well as probability distribution is evaluated. The normal distribution probabilistic model is examined whether it can be used to fit the experimental results for the compressive strength of RAC. The model is verified by Pearson goodness of fit test at 95% confidence level. Finally, the Monte-Carlo simulation technique is performed to obtain the theoretical strength distribution. The simulated distribution is compared with the experimental data.

2. Previous Studies

Very few investigations on the effect of RCA on the statistical parameters of the compressive strength of concrete have been carried out in previous studies. Early studies in Japan implied that the coefficient of variation of the compressive strength of RAC, which was produced in the laboratory, was not much different from NAC when one and the same RCA was used throughout the whole production process (Nihibayashi and Yamura, 1988). This finding was later confirmed and reported that the quality of RCA from crushed concrete specimens produced in the laboratory was relatively uniform, which resulted in a similar variability of the compressive strength of RAC and NAC (Larranaga, 2004). Similar results were also observed by some researches who found the compressive strength of RAC does not vary much from that of normal concrete with similar strength. In all the above experiments, RCAs crushed from laboratory specimens were used.

To more realistically represent the RCA from demolished concrete structures, RCA that was crushed from waste concretes from a concrete pavement was used. On the basis of a large experimental program, the statistical parameters of compressive strength of RAC are investigated. The experimental results indicated that the coefficient of variation of the compressive strength of RAC is not much different from that of NAC under their test conditions, regardless of the RCA replacement percentage. Similar findings were also reported by a scholar who used RCA produced from a concrete plant.

It should be noted that in most of the above tests, only RCA from one single source were used. However, in practice, RCA may come from distinct different sources. For RAC made with RCAs from different sources, the probabilistic distribution characteristics for the compressive strength of the concretes need to be further investigated.

3. Experimental Program

Ordinary Portland cement (OPC) with a 28-day compressive strength of 42.5 MPa and local river sand (fineness modulus 2.75), and water through campus water supply systems in Lishui city are used. Two RCAs were utilized in this study. The first RCA, denoted as RCA1, was prepared by crushing laboratory cast specimens made from original concrete, which has the compressive strength about 43MPa. The second, that is, RCA2 was produced from demolished concrete rubble in Lishui city. The drilled core tests showed that the compressive strength of the concrete rubble is about 37MPa (Xiao, et al., 2008). The natural aggregate is crushed granite. The RCAs and natural aggregate have the similar grading curves, and they meet the corresponding requirement for normal concrete. The basic properties of both natural aggregate and RCA are presented in Table 1. From Table 1, it can be seen that the RCAs have the following characteristics in comparison to natural aggregates: lower bulk and apparent density, higher water absorption ratio and lower strength characterized by larger crushing index (de Paw, 1981). The characteristics are attributed to old mortar adheres to the RCAs.

Due to the high water absorption ratio of RCAs, the mix design method for conventional concrete, cannot be directly used to RAC since it may result in poor workability of the concrete mixtures. In this work, the mixing design procedure proposed for RAC in is used. The mixtures were divided into four groups, namely NAC, RAC1, RAC2 and RAC3. The mainly difference among various mixtures is the used coarse aggregate. For the mixture NAC, only natural aggregate was used, while for mixtures RAC1 and RAC2, the RCA1 and RCA2 were used, respectively. In the last mixture RAC3, both RAC1 and RAC2 were used with a volume ratio of 1:1 (Hansen, et al., 1983). For each mixture, a total of 45 cubes of 150 x150x150mm were prepared considering the need for Pearson goodness of fit test. Table 2 shows the mix proportions and slump for all concrete mixtures.

Table 1: Basic properties of natural and recycled aggregates

Aggregate type	Grading (mm)	Bulk density (kg/m^3)	Apparent density (kg/m^3)	Water absorption (%)	Crushing index (%)
NAC	5-31.5	1450	2894	0.25	3.82
RCA-1	5-31.5	1202	2410	6.25	12.6
RCA-2	5-31.5	1232	2480	4.16	9.8
RCA-3	5-31.5	1218	2442	5.22	11.2

Table 2: Mix proportions and slumps of concrete

Mix	W/C	Materials used in 1m^3 (kg/m^3)					Slump (mm)
		Cement	Sand	Coarse aggregate		Water	
				Natural	Recycled		
NAC	0.39	475	505	1265	-	185	52
RAC1	0.39	521	505	-	1066	185	48
RAC2	0.39	521	505	-	1084	185	50
RAC3	0.39	473	562	-	1093	185	45

The preparation and the cure of all mixtures were conducted in the Laboratory for Building Material Research at Lishui University, PR China. All mixtures are prepared with a 150L mixing machine. The sand, cement and coarse aggregates are placed and mixed for about 2 min before water is added. After 3 min of mixing followed, a slump test is run to determine its workability (Coquillat, et al., 1982). The mixture in each group is cast in steel moulds and then compacted on a vibration table. They are demolded 24h after casting. All the concrete specimens were cured in a standard frog room (202^{0}C and 95% relative humidity) for 28 days before the test. All specimens of NAC and RAC are tested in a universal testing machine to obtain the failure load.

4. Test results and statistical analysis

4.1 Statistical parameters of the tested compressive strength

After testing *N* number concrete cube specimens under the same condition, a series of order strength values can be obtained. The statistical parameters, such as the maximum and the minimum value, and the mean value, the standard deviation and the coefficient of variation for the compressive strength of the concretes are obtained and shown in Table 3.

Table 3: Statistical parameters for the compressive strength

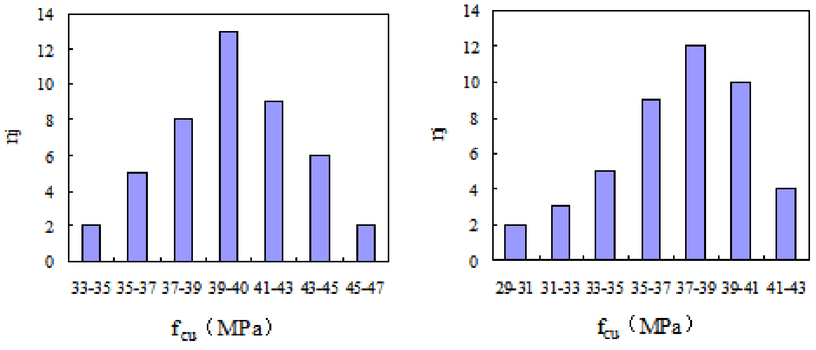
No	$f_{cu,\max}$	$f_{cu,\min}$	$\tilde{f}_{cu}$	$\mu_{f_{cu}}$	$\sigma_{f_{cu}}$	$\delta_{f_{cu}}$ (%)
NAC	45.2	33.8	40.1	39.6	3.34	8.43
RAC1	42.9	29.8	38.3	37.8	3.22	8.52
RAC2	44.4	32.9	39.5	39.4	3.29	8.35
RAC3	43.7	30.2	38.7	38.0	3.43	9.04

It can be seen from Table 3 that the mean compressive strength of RAC is in general lower than that of NAC. For RAC1 and RAC2, the reductions are 3.62% and 5.08 %, respectively; while for RAC3, the strength reduction is 3.96% (Lü, 2000). Several reasons may be responsible for the reduction of the compressive strength, including an increased porosity and a weak aggregate-matrix interfacial bond.

One can see from Table 3 that the standard deviations and the coefficient of variation for the compressive strength of all the three RACs are somewhat higher than that of normal concrete. In addition, the two parameters mentioned above for RAC2 and RAC3 are slight higher than that of RAC1 (Li, 2009). This is because the RCA1 has more uniform quality than RCA2 and RAC3. However, generally speaking, the variability for the three RACs is not much different from those of the reference NAC.

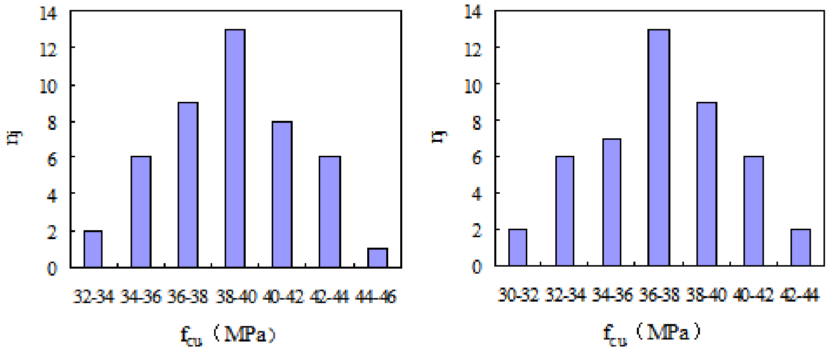
4.2 Probability distribution characteristics of the compressive strength

For conventional concrete, it is generally accepted that the normal distribution model is suitable for describing the probability distribution of the compressive strength. The histograms, which are primarily used for illustrating the distributions of the concrete compressive strength of concrete mixtures, are shown in Fig.1.



(a) NAC

(b) RAC1



(c) RAC2

(d) RAC3

Figure 1: Histogram for the distribution of the compressive strength

It can be seen that the observed strength varies over a wide range (Yen, et al., 1997). From the histograms, it is reasonable to assume a normal distribution to fit the measured data for all the concretes, irrespective of the natural and recycled aggregates. Thus, the normal distribution is tried to fit the data. In order to verify the normal distribution for RACs compressive strength, a Pearson test and a Kolmogorov-Smirnov test are performed.

For the Pearson test, we suppose for normal distribution H_0

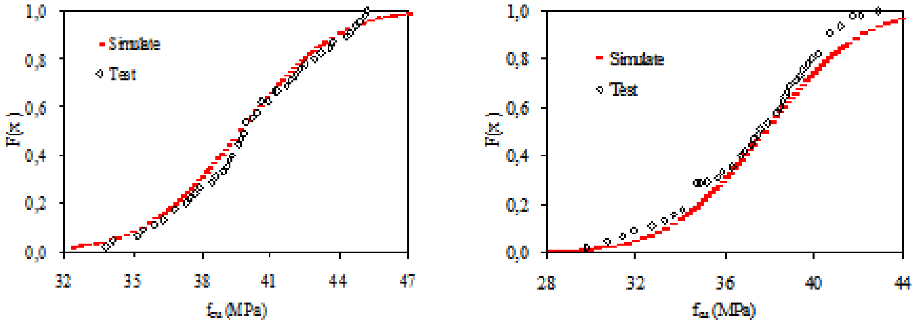
The results of the-test for the distribution of the compressive strength for all the tested concretes are presented in Tables 4. The results in this Table indicate that H_0 for the normal distributions cannot be rejected (Nixon, et al., 1978). Thus, it can be concluded that the normal distributions is able to applied to fit the compressive strength results of all the concretes at a 95% confidence level, irrespective of natural and recycled aggregates.

Table 4: Test results on the normal distribution of compressive strength

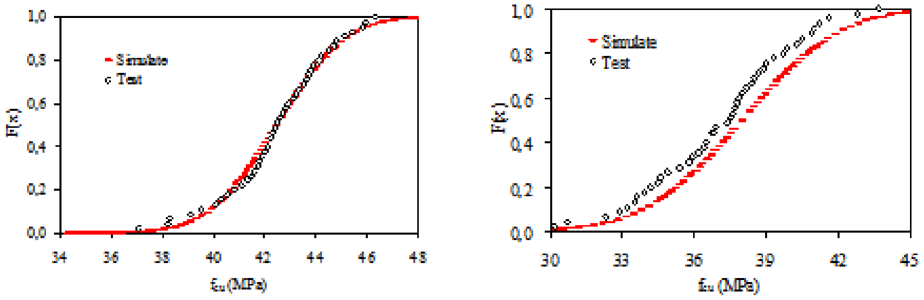
No	-Statistic	-Critical (at 0.05 level, 2-tailed)	Accept / refuse H_0
NAC	4.2379	7.815	Accept
RAC1	7.6089	7.815	Accept
RAC2	4.9288	7.815	Accept
RAC3	6.7227	7.815	Accept

4.3 The Monte-Carlo simulation

Due to the limited test results, a Monte-Carlo simulation study was also conducted. Such simulations have also been carried out in previous studies. The Monte-Carlo method refers to the practice of randomly assigning a value to an underlying random variable or vector, and observing the outcome of the process of interest (Mukherjee and Chakraborty, 2003). Here, the underlying random variable is the compressive strength of the concrete and the process of interest is the probability of failure. The random concrete strength (Xi) is obtained by assigning the cumulative distribution function of the normal model, namely, F(Xi) to a random value ri between 0 and 1. The process is repeated several times to obtain the failure probability, i.e., the number of specimens failed at any stage of loading to the total number of simulations at that stage of loading (Hansen, et al., 1992). The probabilities of the failure, that is, the cumulative distribution function at different stage of loading obtained by experiment and simulation for all the tested concretes are calculated and presented in Figs. 2(a)-2(d). The results from the Monte-Carlo simulation are verified again that the normal distribution can be adopted to describe the compressive strength of the RACs.



(a)NAC (b) RAC1



(c)RAC2 (d) RAC3

Figure 2: Comparison of the test and simulated compressive strength distribution

5. Conclusions

This paper investigates the probability distribution characteristics for the compressive strength of concrete with RCA from two different sources. Within the scope of this study, the following conclusions can be drawn:

The standard deviation and coefficient of variation of the compressive strength of concrete with different RCAs are only slight higher than that of normal concrete.

The normal distribution can be utilized to fit the compressive strength of RAC at 95% confidence level.

The distributions for the compressive strength of RAC do not vary much from that of normal concrete with similar strength, inspection of the RCA from different sources.

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