COMPRESSIVE STRENGTHS OF CONCRETE CONTAINING RICE HUSK ASH WITHOUT PROCESSING

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The effect of rice husk ash (RHA) without processing content on compressive strengths of concrete with different strength grades was studied experimentally at 28 days. The size effect of specimen on compressive strengths was also analyzed and discussed. The results indicate that RHA without processing reduces the cubic compressive strengths of concrete, the brittleness coefficient and the size effect of strengths. With the increase of RHA content, the reduction effect is more and more obvious. There exists a good linear relationship between the brittleness coefficient and the size effect of strengths of concrete. Based on the brittleness coefficients, the size effect law is proposed, which can well predict the size effect of cubic compressive strengths of concrete. RHA without processing increases the volume fractions of porosity and high-density calcium silicate hydrates, but reduces the volume fractions of calcium hydroxide.

Keywords: *concrete, rice husk ash without processing, cubic compressive strength, size effect, brittleness*

1. Introduction

China is the largest rice production country of world. The total paddy output of China reached 207 million tons in 2016, 20% of which was rice husks. Nowadays, the traditional resources such as oil and gas are increasingly scarce, so rice husk is widely burned to generate electricity in the thermal power plants. Meanwhile, a large amount of rice husk ash (RHA) is also produced by burning. RHA is discharged as solid waste for a long time, which leads to the low utilization of recycling. In addition, RHA occupies a great deal of arable land and pollutes the surrounding ecological environment. In order to solve the problems above, the utilization of RHA with high additional value becomes quite urgent [1].

RHA contains a lot of amorphous silicon dioxide (SiO_2). It can react with calcium hydroxide (CH) which is produced by cement hydration. The reaction produces are additional calcium silicate hydrates (C-S-H) which improve effectively the properties of concrete [2]. Compared to the traditional mineral admixtures such as silica fume, fly ash, slag and metakaolin, RHA is a kind of relatively ideal mineral admixture.

Hence, the preparation of concrete with RHA becomes gradually one of the main technologies for recycling [1, 2]. At present, RHA used as cementitious material is mainly obtained by grinding and calcinations at low temperature to assure a high activity. The strict control condition may leads to the low output. The technical parameter of this kind of RHA is completely different from that of RHA obtained from the natural incineration without grinding, named as RHA without processing. There is a considerable output for RHA without processing. It has coarse particles, low activity and however, the application of RHA without processing in concrete is also feasible [3, 4]. Therefore, it is important to study the properties of concrete containing RHA without processing systematically.

The size of concrete piece in practical engineering is much larger than that used in the lab. Hence, the size effect on properties of concrete should be considered. Most of study mainly focused on the effect of different concrete components [5-7]. However, the effect of mineral admixtures and of the size specimens on concrete strengths was rarely studied.

Based on the analysis above, the effect of RHA without processing content on compressive

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Table 1

Chemical compositions of cement and RHA without processing (wt %)

Materials	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_2	P_2O_5	LOI
Cement	24.32	6.14	5.16	62.17	1.50	-	-	-	-	0.71
RHA	82.22	1.47	1.26	2.73	0.61	4.33	0.20	0.50	0.52	6.16

strengths of concrete with different strength grades was investigated systematically. The size specimen effect on compressive strengths of concrete containing RHA without processing was also studied. The relationship between the brittleness coefficient and the size effect degree of compressive strengths was established. The size effect law on compressive strengths of concrete was also proposed and the mechanism was revealed by the nanoindentation technique. The conclusions of the paper can help to spread the application of RHA without processing.

2. Experimental

2.1. Materials

The cement used in the present study was ordinary Portland cement with the strength grade of P·O42.5 in accordance with Chinese standard GB 175-2007. The RHA without processing was obtained by the natural incineration without grinding in Jingzhou City, Hubei Province, China. The appearance is given in Figure 1.

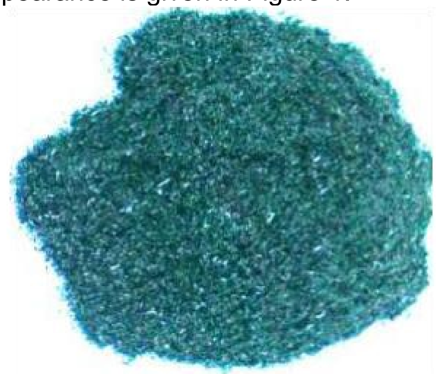


Fig.1- Appearance of RHA without processing

Table 1 shows the chemical compositions of cement and RHA without processing, which exhibits that the content of SiO_2 of RHA without processing is about three times more than that of cement, and the content of loss on ignition (LOI) is also more than that of cement, but the content of CaO is significantly less than that of cement.

In addition, the grain composition and particle size distribution of cement and RHA without processing were determined by laser particle analysis using BT-9300 Laser Particle Analyzer. The results are shown in Figure 2, which shows the mean particle sizes of cement and RHA without processing are 12.52μm and 48.74μm, and the particle size range of RHA without processing is very narrow, focusing on the range from 13.77μm to 117.13μm.

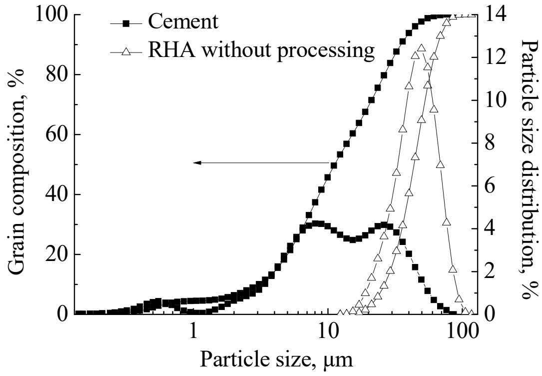


Fig.2- Grain composition and particle size distribution of cement and RHA

River sand was used as fine aggregate, which has a fineness modulus of 2.3 and a specific gravity of 2545 kg/m^3. Crushed limestone was used as coarse aggregate, which has a size range from 5.0mm to 25mm, and a specific gravity of 2645 kg/m^3. In order to adjust the workability of concrete containing RHA without processing, the polycarboxylic superplasticizer (SP) with water-reducing range of more than 25% and solid content of about 30% by weight was also used.

2.2. Concrete mixture proportioning

The concrete containing RHA without processing was prepared with two strength grades, i.e. C30 and C60, which represented the most used concrete and the high-strength concrete, respectively. For the concrete with the same strength grade, the water to binder ratio (w/b), fine to coarse aggregate ratio and unit water consumption were kept as constants. RHA without processing was added to replace cement by weight (10%, 20% and 30% of binder). The SP content was controlled to maintain the similar pump ability of concrete. Concrete cube specimens with three sizes (100mm, 150mm and 200mm) were casted. For each cube size concrete, three specimens were prepared. Hence, the tests had a total of 72 concrete specimens. The details of the components used in concrete containing RHA without processing mixtures are shown in Table 2.

2.3. Test methods

For the compressive strength tests, the concrete specimens were kept in moulds for about 24 hours after mixing and casting. Then they were demoulded and placed in a room for another 27 days to cure (28 days from mixing to testing). In order to simulate the service status of practical concrete engineering, the natural curing was

Table 2

Mix proportions of concrete containing RHA without processing (in weight - kg)

Strength grade	Mixture indicative	Cement	RHA	River sand	Crushed limestone	Water	SP
C30	C30-0	340	0	763	1144	153	3.4
	C30-10	306	34	763	1144	153	6.2
	C30-20	272	68	763	1144	153	7.5
	C30-30	238	102	763	1144	153	9.2
C60	C60-0	500	0	700	1050	150	7.3
	C60-10	450	50	700	1050	150	8.6
	C60-20	400	100	700	1050	150	9.4
	C60-30	350	150	700	1050	150	12.1

adopted, and the corresponding curing temperature and humidity are shown in Figure 3. It can be seen that the variation range of curing temperature is from 13.5°C to 25°C, and that of humidity is from 46% to 98%, whose fluctuation ranges of some ages are great. The compressive strength tests were carried out by STYE-3000E press machine. In order to eliminate the effect of loading rate on the compressive strengths, the loading rates were kept as constants, i.e. 0.5MPa/s.

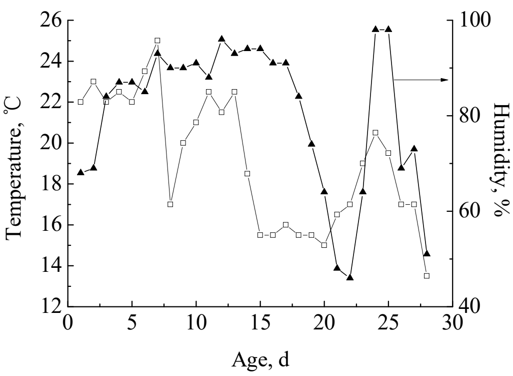


Fig.3- Curing temperature and humidity of natural curing.

In order to reveal the mechanism of RHA without processing effect on properties of concrete from the nano-scale structure perspective, the nanoindentation technique was carried out to evaluate the distribution of elastic modulus of matrix in C60 concrete. The detailed test procedures can be found in our published literatures [8, 9].

3. Results and discussions

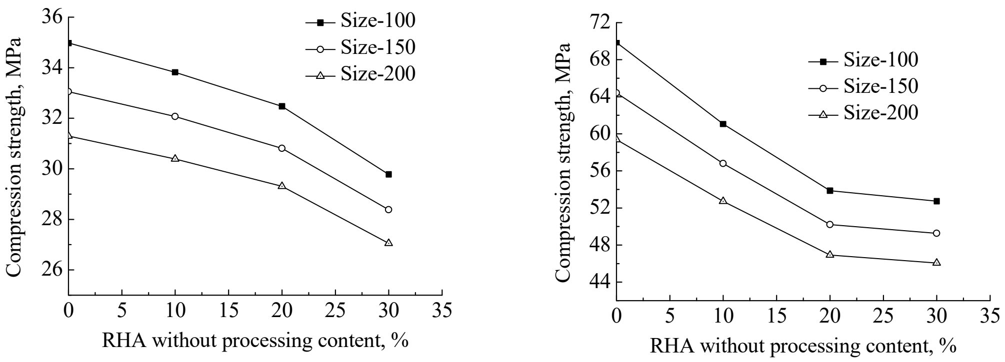
3.1. Compressive strength of concrete

Table 3 shows the variation of compressive strengths of concrete containing RHA without processing at 28 days. Based on the strength grades of concrete, the content of RHA without processing replacing cement by weight, and the sizes of specimens, the indicative of compressive strengths were designated as Ca-b-c. The Ca in the designation represented the strength grades of concrete, b represented the content of RHA without processing, and c represented the size of the specimen. For example, C30-10-100 meant 100 mm cubic C30 concrete with 10% RHA without processing.

Table 3

Cubic compressive strengths of concrete containing RHA without processing

Specimen indicative	Cubic compressive strength (MPa)	Standard deviation (MPa)	Coefficient of variation (%)
C30-0-100	34.98	1.7	4.90
C30-0-150	33.05	1.12	3.41
C30-0-200	31.30	0.98	3.13
C30-10-100	33.82	0.63	1.86
C30-10-150	32.07	1.76	5.48
C30-10-200	30.39	1.21	3.98
C30-20-100	32.47	1.58	4.86
C30-20-150	30.81	0.63	2.02
C30-20-200	29.31	1.22	4.09
C30-30-100	29.78	1.07	3.63
C30-30-150	28.38	1.42	4.97
C30-30-200	27.05	0.72	2.63
C60-0-100	69.86	3.41	4.88
C60-0-150	64.41	2.35	3.66
C60-0-200	59.38	3.64	6.13
C60-10-100	61.07	2.72	4.55
C60-10-150	56.80	1.69	2.97
C60-10-200	52.72	3.07	5.82
C60-20-100	53.87	3.22	6.05
C60-20-150	50.21	2.69	5.30
C60-20-200	46.92	1.81	3.85
C60-30-100	52.74	2.71	5.29
C60-30-150	49.27	3.06	6.14
C60-30-200	46.07	3.02	6.34



(a) C30 (b) C60

Fig.4- Effect of RHA without processing content on compressive strengths of concrete

Table 4

Size effect degrees of compressive strengths and brittleness coefficients of concrete containing RHA without processing

Index	C30-0	C30-10	C30-20	C30-30	C60-0	C60-10	C60-20	C60-30
△α150(%)	5.52	5.19	5.11	4.70	7.80	6.99	6.79	6.58
△α200(%)	10.52	10.15	9.74	9.16	15.01	13.67	12.90	12.64
β	8.21	8.09	7.93	7.61	11.47	10.77	10.12	10.03

In Table 3 it can be seen that the discreteness of compressive strengths is small, and the coefficients of variation are less than 8%, which indicates the good preparation technology of concrete containing RHA without processing. Based on the results of Table 3, the effect of RHA content on the compressive strengths of concrete at 28 days is shown in Figure 4.

It can be found that compressive strengths of concrete at 28 days diminish continually with the increase of RHA content. Their effect on the higher strength grade concrete (C60) is more obvious. For example, by comparing of the compressive strengths of C30 and C60 control concrete - samples with the size of 150 mm cube, 30% RHA reduces by 14.1% and 23.5%, respectively. This finding seems to be consistent to what was reported in literatures. Rukzon et al. [10] found that the compressive strength of the mortar containing one type of RHA0 (the original RHA with 75% remainder on a 325# sieve) was lower than that of the control mortar at all ages. At the age of 28 days, the strength of the RHA0 mortar was 55% of that of the control mortar at the same age. Another type of RHA1 (the RHA was obtained using ball mill grinding until the percentage remainder on a 325# sieve was 30%) had the strength activity index of at least 75% of the control mortar at the age of 28 days when it was used to replace 20% of Portland cement. Therefore, RHA1 could be used as a pozzolana to replace part of Portland cement in making the mortar with relatively high strength. However, there are also inconsistent results. Chopra et al. [11] reported that the increases of about 25% strength at 7 days, 33% strength at 28 days and 36% strength at 56 days were observed for an addition of 15% RHA as cement replacement. When the RHA content was more than 15%, there was a decrease in strength due to lower cement content. This may be attributed to the different varieties, activities and particle sizes of RHA as well as curing conditions. In addition, it can be seen in Figure 4 that with the increase of RHA content, the compressive strength differences among concretes with different sizes diminish gradually, which indicates that the size effect on compressive strengths of concrete containing RHA without processing also diminishes gradually.

3.2. Brittleness coefficient of concrete

It is generally believed that the size effect of specimen on strength is related to its brittleness. The brittleness coefficient of concrete can be defined as the ratio of compressive strength to flexural strength. With the decrease of brittleness coefficient value, the brittleness of concrete is improved. According to the relationship between the compressive strength and flexural strength of concrete reported by Collepardi [12], the relationship between the compressive strength and brittleness coefficient of concrete can be obtained as follows:

$$\beta = 0.7\sqrt{f_{cu,150}} \qquad (1)$$

where β is the brittleness coefficient of concrete.

Based on the results in Table 3, the brittleness coefficients of cubic concrete specimens containing RHA without processing can be calculated, which are shown in Table 4. It is observed that RHA without processing reduces the brittleness coefficient of concrete, and the brittleness coefficients increase with the increase of strength grade of concrete.

3.3. Size effect of compressive strengths

3.3.1. Size effect degree

Size effect degree is one of indexes which can represent the size effect on properties of concrete. Assume that the control size of cubic concrete specimen is 100 mm, and non-control sizes are 150 mm and 200 mm, respectively. The size effect degree is defined as the ratio of the compressive strength differences between the control size and non-control size to the compressive strength of the control size. It can be calculated as follows:

$$\Delta\alpha_{150} = \frac{f_{cu,100} - f_{cu,150}}{f_{cu,100}} \times 100\% \qquad (2)$$

$$\Delta\alpha_{200} = \frac{f_{cu,100} - f_{cu,200}}{f_{cu,100}} \times 100\% \qquad (3)$$

where △α150 and △α200 are the size effect degrees of compressive strengths of 150 mm and 200 mm cubic concrete specimens, and $f_{cu,100}$, $f_{cu,150}$ and $f_{cu,200}$ are the compressive strengths of 100 mm, 150 mm and 200 mm cubic concrete specimens, respectively.

Based on the results in Table 3, the size effect degrees of compressive strengths of cubic concrete specimens containing RHA without processing can also be calculated as is shown in Table 4.

It can be seen in Table 4 that the size effect degree on compressive strength of 200 mm cubic concrete specimen containing RHA without processing is greater than that of 150 mm cubic concrete specimen. The higher strength grade concrete (C60) containing RHA without processing has the greater size effect degree.

In addition, it can also be observed that RHA without processing reduces the size effect degrees of cubic compressive strengths and brittleness coefficients. In order to obtain the relationships between the size effect degree and brittleness coefficient, the fitting analysis is carried out. The results are shown in Figure 5.

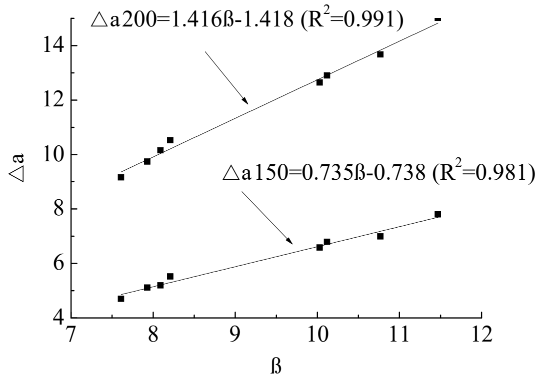


Fig.5- Relationships between the size effect degree and brittleness coefficient

It can be seen in Figure 5 that the size effect degree and brittleness coefficient show a good linear relationship, which can be expressed as follows:

$$\Delta\alpha = a \times \beta + b \qquad (4)$$

where *a* and *b* are constants, which depend on the sizes of cubic concrete specimens. The value of *a* reflects the change speed of △α with the change of *β*. The value of *b* is the size effect degree, when the brittleness coefficient is zero. Actually, the brittleness coefficient is not likely to reduce zero. The size effect degree increases with the increase of the brittleness coefficient.

3.3.2. Size effect law

There are many theories on the size effect of concrete strengths. Among them, the size effect theory proposed by Bažant [13] has a significant effect. The main ideal is that the size effect of quasi-brittle materials is caused by the expansion and dissipation strain energy of crack under the pressure again before the maximum load. Based on the size effect theory of the energy release, Bažant [13] proposed the size effect law of the nominal strength (δ_N) during the failure of specimen under pressure. It is expressed as follows:

$$\delta_N=\delta_\infty(1+D_b/D). \qquad (5)$$

where δ_∞ and D_b are constants, which are the nominal compressive strength and structural characteristic size of specimens with the maximum sizes, respectively; *D* is the size of the specimen.

Based on the results in Table 3 and Table 4, δ_∞ and D_b can be obtained, which are shown in Table 5.

Similarly, the test result data in the literatures [5, 14-16] are substituted into the equations (1) and (5), so β, δ_∞ and D_b can also be obtained. The aforementioned β, δ_∞ and D_b are carried out the fitting analysis to obtain the relationships among them, which is expressed as follows:

$$\delta_\infty=4.729e^{0.209\beta} \qquad (6)$$

$$D_b=4.799\beta-13.348 \qquad (7)$$

The equations (6) and (7) are substituted into the equation (5). Based on the brittleness coefficients, the size effect law of cubic compressive strengths of concrete can be obtained, which is expressed as follows:

$$\delta_N=4.729e^{0.209\beta}[1+(4.799\beta-13.348)/D] \qquad (8)$$

Table 5

δ_∞, D_b and β of concrete containing RHA without processing

β	8.21	8.09	7.93	7.61	11.47	10.77	10.12	10.03
δ_∞ (MPa)	31.23	26.06	24.28	22.91	51.28	47.16	41.86	39.22
D_b (mm)	28.49	27.46	25.94	25.12	41.07	36.04	33.74	33.85

The comparison analysis of both test results and calculated values by the equation (8) in the literatures [7, 17-19] are carried out, which are shown in Figure 6. It can be seen from Figure 6 that the errors of both test results and calculated values are with 15%. It indicates that the size effect law can accurately and steadily predict the size effect of cubic compressive strengths of concrete.

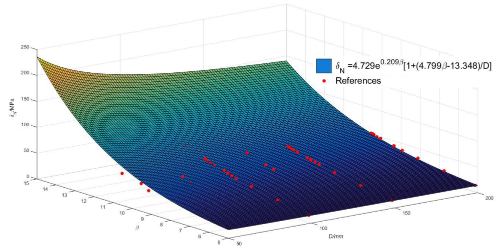


Fig.6- Comparison of size effect law in this study and literatures [7, 17-19]

According to the equation (8), with the increase of cube sizes of concrete to a certain degree, the reduction rate of compressive strengths of concrete is becoming smaller and smaller. Hence, the critical size and strength of concrete can be defined. When the geometric size of concrete is greater than one specific value (D_{cs}), the slope of tangent of one point in the size effect law curves obtained by the equation (8) is greater than -0.01 and the D_{cs} is defined as the critical size of concrete. The corresponding strength is called as the critical strength of concrete (f_{cs}). Based on the definitions, when the size of concrete is less than D_{cs}, the size effect of concrete strength is obvious, and otherwise the size effect is little which can be ignored. Therefore, the critical cubic size and compressive strength of concrete with the different β can be obtained by the equation (8), which is shown in Table 6.

It can be seen in Table 6 that with the increase of brittleness coefficient, the critical size and strength increase gradually. For example, the critical cubic size of concrete with the brittleness coefficient of 12 is 2.42 and 1.54 times the size of those of concrete with the brittleness coefficients of 7 and 9, respectively. It indicates that the affected size range of size effect of compressive strengths increases with the increase of the brittleness coefficients. There is a direct relationship between the brittleness and size effect of the strengths.

3.4. Nanoindentation investigation

Firstly, the matrix of specimens was found with the help of the optical microscope of nanoindentor. A 10×10 grid containing 100 points was carried out on each specimen, and the distance between two adjacent test points was 20ìm. The area was chosen to be statistically representative of the matrix of each specimen. In order to improve the accuracy of results, the respective two areas with in total of 200 points of each specimen were tested. In general, the matrix of concrete consists of four main phases including porosity, C-S-H, CH and unhydrated grains such as cement and mineral admixtures. In addition, the existence of two forms of C-S-H is found because of the different elastic modulus [20], that is, low-density C-S-H (LD C-S-H) and high-density C-S-H (HD C-S-H), respectively. Each phase has a corresponding elastic modulus ranges which are intrinsic mechanical properties. The intrinsic elastic modulus of porosity, LD C-S-H, HD C-S-H and CH are in the range of 0-13GPa, 13-22GPa, 22-33GPa and 33-40GPa, respectively [21], and the intrinsic elastic modulus of unhydrated grains are more than 40GPa [22]. When the test results of unhydrated grain phases in the matrix are ignored, the effect of RHA without processing on the distributions of porosity and hydration product phases is obtained, which is shown in Figure 7.

Based on the results in Figure 7, the volume fractions of each phase in porosity and hydration product phases are also obtained, shown in Table 7.

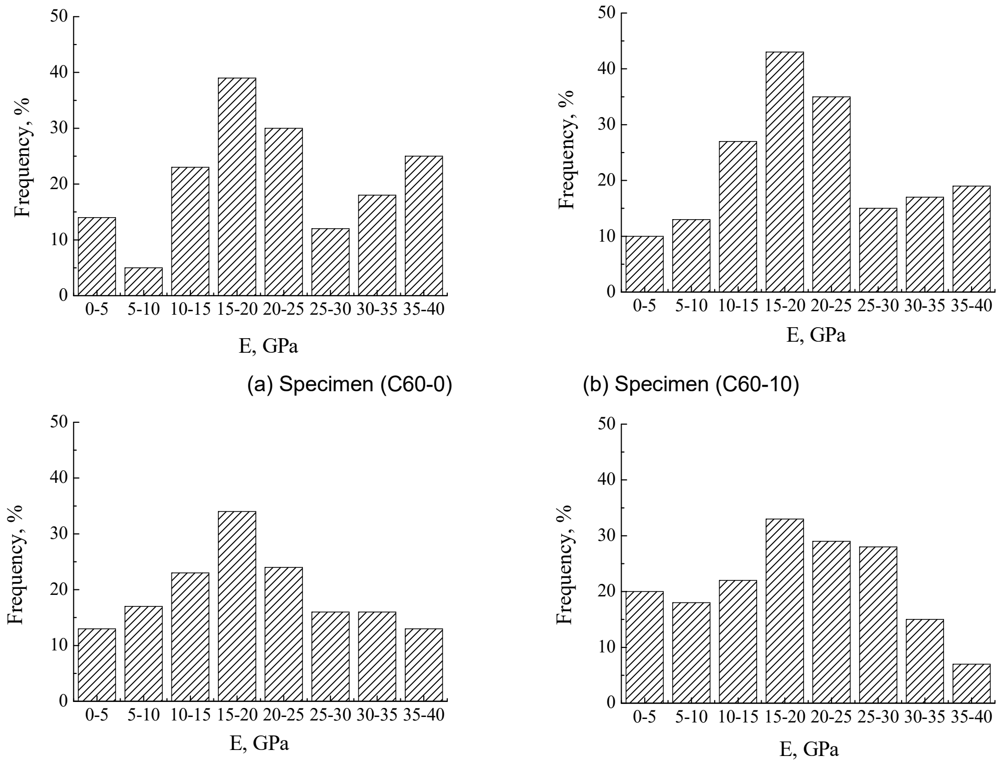
It can be seen that with the increase of RHA without processing content, the volume fractions of porosity are increased, which indicates that RHA without processing reduces the compressive strengths of the specimens, as is shown in Figure 4. However, the volume fractions of CH are reduced. This should mainly be attributed to the fact that the amount of cement replaced by RHA without processing are reduced and part of CH is consumed because of the pozzolanic reaction of RHA without processing. In addition, the volume fractions of HD C-S-H are also increased with the increase of RHA without processing content, and however, the volume fractions of LD C-S-H are reduced basically.

In general, HD C-S-H has better mechanical properties than LD C-S-H, so the comprehensive properties of cementitious materials can be

Table 6

D_{cs} and f_{cs} of concrete with the different β

β	7	8	9	10	11	12
D_{cs} (mm)	203.4	261.2	319	376.8	434.6	492.4
f_{cs} (MPa)	24.34	31.36	38.38	45.4	52.42	59.44



(a) Specimen (C60-0) (b) Specimen (C60-10)

(c) Specimen (C60-20) (d) Specimen (C60-30)

Fig.7- Effect of RHA without processing on frequency histogram of elastic modulus of specimens

Table 7

Volume fractions of each phase in porosity and hydration product phases (%)

Specimens	Porosity	LD C-S-H	HD C-S-H	CH
C60-0	33	70	26	37
C60-10	41	78	33	27
C60-20	42	61	35	18
C60-30	45	54	62	11

improved by increase the amount of HD C-S-H or the volume fraction of HD C-S-H in C-S-H of specimens [23]. According to the results of Table 7, the volume fraction of HD C-S-H in C-S-H of each specimen can be calculated, and those of the specimen (C60-0), (C60-10), (C60-20) and (C60-30) are 27.08%, 29.73%, 36.46% and 53.45%, respectively. It can be seen that with the increase of RHA without processing content, the volume fractions of HD C-S-H in C-S-H are increased. The specimen with 30% RHA without processing has the maximum the volume fraction of HD C-S-H in C-S-H which is nearly 2 times the size of that of the control specimen. Hence, from nano-scale structure perspective, it is inferred that RHA without processing can improve part properties of concrete to some extent due to the increased volume fractions of HD C-S-H in C-S-H.

4. Conclusions

(1) RHA without processing reduces the cubic compressive strength of concrete at 28 days. With the increase of this RHA content, the strengths of concrete are reduced more and more obviously, especially for concrete with the higher strength grade.

(2) RHA without processing can reduce the brittleness coefficient and the size effect degree of strengths of concrete, which increase with the increase of strength grades. There exists a good linear relationship between the brittleness coefficient and the size effect degree of strengths of concrete.

(3) The size effect law ($\delta_N=4.729e^{0.209\beta}[1+(4.799\beta-13.348)/D]$) is proposed, which can well predict the size effect of cubic compressive strengths of concrete. With the increase of the brittleness, and the critical size and strength of concrete are increased.

(4) RHA without processing increases the volume fractions of porosity and HD C-S-H, and reduces the volume fractions of CH. More importantly, it increases the volume fractions of HD C-S-H in C-S-H.

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