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Effect of Particle Size on Properties of Concrete with Rubber Crumbs

Yang He[1, 2, *], Fei Xu[1, 2], Hua Wei[1, 2]

[1]Nanjing Hydraulic Research Institute, Ministry of Water Resources, Ministry of Transport & National Energy of Administration, Nanjing China

[2]Research Center on New Materials in Hydraulic Structures, Ministry of Water Resources, Nanjing, China

Email address:

yhe@nhri.cn (Yang He)

[*]Corresponding author

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Abstract: The number of waste tires is increasing in recent decades. Landfilling and incineration are not only consuming the land resources, but also severely endangered the ecological environment and human health. Therefore, how to recycle waste tires effectively becomes an urgent issue. Certain researches have established that crushing waste tire into powders and adding them in concrete mixer can improve the brittleness and durability of concrete materials. In this paper, the workability, mechanical properties and durability of concrete with rubber crumbs (RCC) were studied. Fine aggregate (FA) was replaced by rubber crumbs of 6 particle sizes, the usage equaled the 10% volume of the FA. The microstructure and pore structure of RCC are analyzed by SEM and MIP. The test results revealed: (1) Due to the difference of air entrainment and absorption, rubber crumb with different particle sizes has different effects on the workability of concrete mixture; (2) The addition of rubber crumbs reduced the strength of concrete, but the relationship between strength and particle size was not monotonous. The compressive strength of RCC decreased at first, then increased with the increase of particle size; (3) The air entraining effect of rubber powder can improve the frost resistance of concrete; (4) The changes of micro morphology and pore structure led to the modification of performances of RCC.

Keywords: Rubber Crumb, Concrete, Durability, Mechanical Property, Pore Structure

1. Introduction

How to effectively recycle waste tires has become an urgent problem to be solved all over the world. At present, the disposal of waste tires in China are mainly recycled rubber and rubber powder, accounting for 71% and 7.5% respectively of the total recycling tires [1-2]. However, recycled rubber caused severe environmental pollution in the production process. Therefore, more and more experts believed that the rubber powder industry represents the development direction of resource utilization of waste tires [3], which could have a broad market prospect. In recent years, plenty of industries began to use rubber powder to produce color composite rubber floor tiles, which could be applied in waterproof or anti-static situations [4]. The rubber powder could be manufactured as the composite coating and used in exterior wall coating. RCC, of course, was an effective method to consume recycling waste tires. Crushing waste tires into rubber particles and adding them into concrete according to a certain proportion can effectively improve the elastic property and durability of concrete, but the selection of particle size of rubber crumb, and how to achieve the best optimization effect remains to be systematically studied.

In recent years, there have been a plenty of practical engineering applications of RCC abroad [5-8], mainly focusing on road, bridge and railway engineering. It had been used as pavement material of road and bridge, which could enhance the resistance of impact, fatigue and wearing. Additionally, compared with ordinary Portland concrete (PC), RCC demonstrated a better property of resisting chemical corrosion of various external environments [9], which prolonged the service life of road and bridge by improving the anti-aging ability of road surface. Besides, the RCC pavement could provide greater friction and reduce driving noise for vehicles by reducing energy consumption and vibration, it greatly optimized the driving safety [10]. Therefore, rubber concrete is an ideal material for road and bridge engineering. However, due to the lack of research on RCC in China and the negative impact of rubber powder on the mechanical properties of concrete, there are few practical engineering application of RCC in China. In this paper, the workability, mechanical properties and durability of rubber concrete mixture are analyzed through experiments, which provides a reference for the further study of the performance and application of rubber concrete.

2. Materials & Mix Proportion

2.1. Materials

(1) Cement: P·O 42.5 ordinary Portland cement (Anhui Conch Cement Co., Ltd.) is used. The chemical composition, physical properties are shown in Tables 1 and 2.

Table 1. *Chemical composition of cement.*

Composition	SiO_2	CaO	MgO	Fe_2O_3	Al_2O_3	Na_2O	K_2O	SO_3
Mass fraction	21.20 %	61.18 %	1.90 %	3.36 %	5.89 %	0.15 %	0.57 %	2.24 %

Table 2. *Physical properties of cement.*

Density	Specific surface area	Flexural strength		Compressive strength	
		3d	28d	3d	28d
3.15 g/cm^3	3400 cm^2/g	5.9 MPa	9.1 MPa	30.4 MPa	51.3 MPa

(2) Aggregate: Natural quartzite sand and limestone are respectively used as fine and coarse aggregate. The maximum particle size of coarse aggregate used in this paper is no more than 31.5mm, and the particle grading is up to the standard of continuous grading referred in GB/T 14685 [11]. The fineness modulus of fine aggregate is 2.7. The properties of aggregates are shown in Table 3.

Table 3. *Properties of aggregate.*

	Apparent density	Bulk density	Fineness modulus	Particle size	Crushing index
Fine aggregate	2600 kg/m^3	1450 kg/m^3	2.7	≤5 mm	/
Coarse aggregate	2720 kg/m^3	1480 kg/m^3	/	5~31.5 mm	8.2 %

(3) Plasticizer: FDN superplasticizer (Sobute New Materials Co., Ltd.) is used. The water reduction rate is 20%. The form is brown solid powder.

(4) Rubber crumbs: The particle sizes of RC are 4mm, 1.7mm, 0.83mm, 0.38mm, 0.18mm and 0.12mm. The density of RC is 1100 kg/m^3. The shape of RC is shown in Figure 1.

Figure 1. *Particle sizes of rubber crumbs.*

2.2. Mix Proportion

Table 4 describes mix designs of RCC. The rubber crumbs, content of all particle sizes, replace 10% of the volume of fine aggregate in the concrete mixture. The water to cement ratio (W/C) was designed as 0.52. The plasticizer weights as 1.5% as the cement. The sand aggregate ratio of concrete mixture is 0.38.

Table 4. *Mix proportion per cubic meter of RCC (kg/m^3).*

Notation	Cement	Fine aggregate	Coarse aggregate	Plasticizer	Water	Rubber crumb (particle size)
PC	327	712	1162	4.90	170	0
RCC-120	327	641	1162	4.90	170	30 (0.12 mm)
RCC-80	327	641	1162	4.90	170	30 (0.18 mm)
RCC-40	327	641	1162	4.90	170	30 (0.38 mm)
RCC-20	327	641	1162	4.90	170	30 (0.83 mm)
RCC-10	327	641	1162	4.90	170	30 (1.7 mm)
RCC-5	327	641	1162	4.90	170	30 (4.0 mm)

3. Experiment

3.1. Workability

(1) Fluidity

It could be shown that the cohesion and water retention of the mixture of PC/RCC were good, and there was no segregation and bleeding. The slump of the reference concrete mixture was 90mm, and the test results of the slump of the rubber concrete mixture are shown in Figure 2(a).

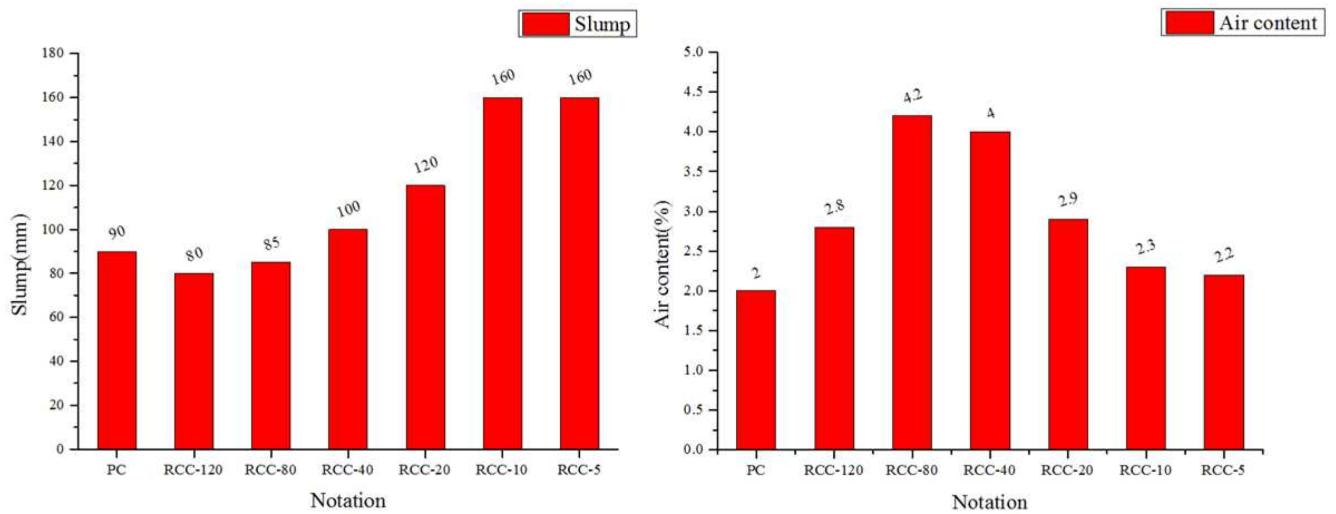
As can be seen from the Figure 2(a), the slump of concrete mixture with the RC particle size of 0.12mm and 0.18mm could be reduced. However, if the particle size is greater than 0.38mm, the slump increased with the increase of particle size.

The air entrainment and moisture absorption of rubber crumbs caused such changes in slump of concrete mixture [12]. From one side, due to the air entrainment of rubber particles, bubbles are introduced during concrete mixing. The bubbles wrap on the outer surface of rubber particles and form a ball effect with concrete mortar, so as to reduce the friction between them and increase the fluidity. This explained the reason why the slump increased. On the other hand, though the rubber crumbs are hydrophobic materials, water can still adhere to its surface easily due to the porous structure, this kind of absorption effect consumes a certain amount of water in the mixture, in that way, causes the decline of fluidity.

In conclusion, different RC sizes could lead to changes in air entrainment and water absorption effect. Air entrainment effect had a positive impact on fluidity, while water absorption had a negative one. Therefore, the workability of RCC mixture depended on the combination of these two sides mentioned above.

(2) Air content

Air content is another important index of workability of concrete mixture, and it is closely related to many properties of hardened concrete. The air content of PC mixture was 2.0%, and the test results of air content of all the test concrete mixture are shown in Figure 2(b).



(a) Slump (b) Air content

Figure 2. Workability of the concrete mixture.

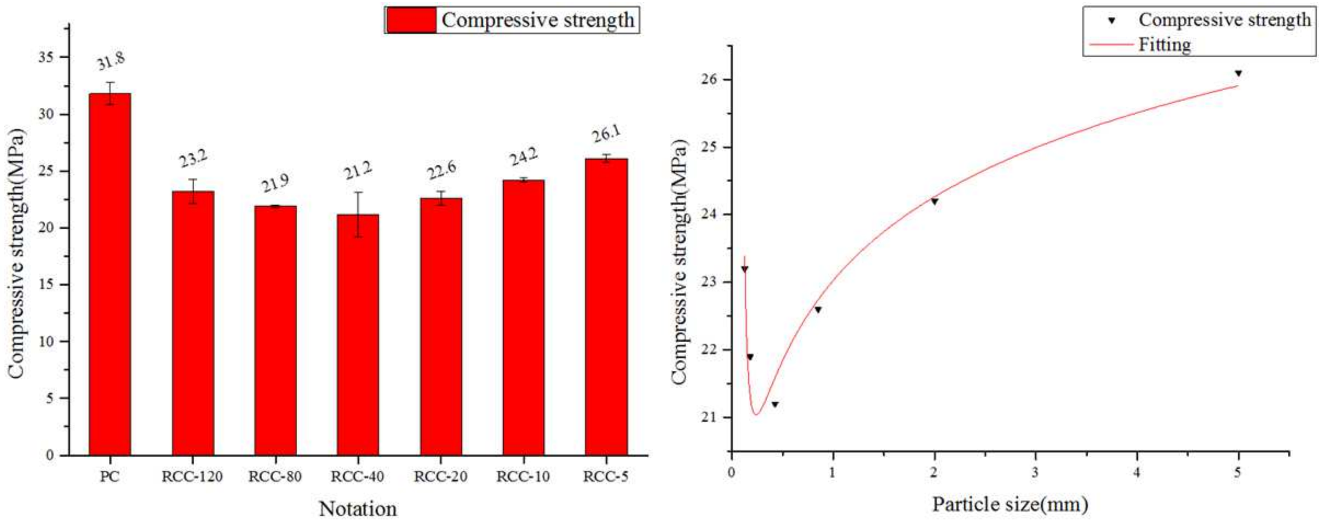
According to the test results, when the RC particle size was less than 1.7mm, the air content of RCC mixture could be significantly improved. Once the rubber particle size was greater than 1.7mm, there was almost no difference in air content compared to PC mixture.

It was sort of given that the small particle size of RC possessed larger specific surface area and rougher the surface than the big one, which brought more air contented in the mixture. However, the test result shown that there was no linear relation, even not a monotonic one, between the air content of the mixture and the particle size of RC. When the RC content is 10% volume of the fine aggregate, the air content increased at first and then decreased with the larger of particle size. When the particle size of RC was 0.18mm, the air content reached the highest value among all the mixture in the research. The phenomenon mainly because the moisture absorption of RC was significantly enhanced when the particle size was smaller than a certain value. The effect reduced the fluidity of the mixture and made the process of air entrainment more difficult.

3.2. Mechanical Properties

(1) Compressive strength

According to the mixture proportion in Table 4, each batch fabricated 3 cubic concrete specimens for compressive strength test. The average strength of specimens represented the compressive strength of concrete. The influence of rubber particle size on concrete compressive strength was shown in Figure 3. The compressive strength test used cubic test specimens with the edge length of 150mm. The curing age was 28 days with the curing method according to the standard for test methods of concrete physical and mechanical properties (GB/T 50081-2019). What can be easily drawn from the result was that as the larger of the particle size of RC, the compressive strength of concrete decreased first and then increased. The min value appeared at the batch of RCC-80, also the most air content batch mentioned above. Obviously, the high air content counted the most important factor for the decline of compressive strength. The available literature evidenced [13] that for every 1% increase in air content, the compressive strength of concrete decreased by about 5%.



(a) Compressive strength (b) Compressive strength – particle size fitting

Figure 3. *Mechanical properties of RCC.*

Assuming the RC particles shaped in a cube structure (considered the crushing and grinding process of wasted rubber productions), the volume of a single particle of RC could simulate as the cube of its edge length. According to the premise, the relationship between the 28d compressive strength of RCC and the particle size of RC could be obtained. The fitting curve was shown in Figure 3(b) and the fitting formula is presented below:

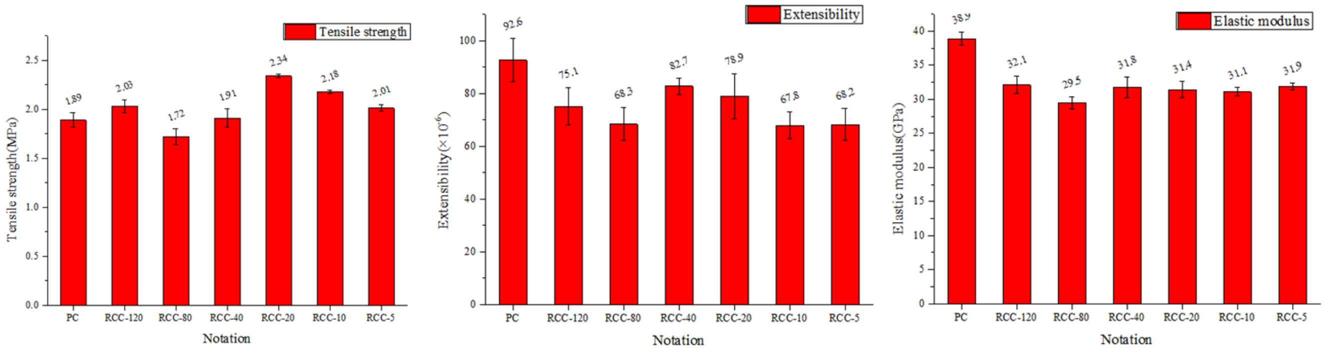
$$F_c = \frac{0.008}{e^3} + 0.6\ln(e^3) + 23.02,\ R^2 = 0.9365 \quad (1)$$

In the formula, F_c represents the compressive strength of RCC; e represents the edge length of an individual RC cubic particle as the e^3 represents the volume of it. This formula revealed the numerical relationship between particle size and compressive strength of RCC.

(2) Tensile properties

The specimens of tensile test are fabricated in shape of prism. The three-dimensional size are 100 mm × 100 mm × 550 mm. Each batch have 3 specimens. During the tensile process of RCC specimen, due to the stress concentration in the internal defects or weak areas, the original micro cracks expanded and new cracks occurred. As an elastomer, RC particles have certain tensile capacity, in that way, RCC could bear a part of the load and prevent the further expansion of micro cracks and the emergence of new cracks, so as to improve the elastic deformation capacity of concrete materials.

Figure 4 shows the tensile properties of RCC with different size of RC particles. On the whole, there was no concordant regulation among the tensile strength, extensibility and elastic modulus.



(a) Tensile strength (b) Extensibility (c) Elastic modulus

Figure 4. *Tensile properties of RCC.*

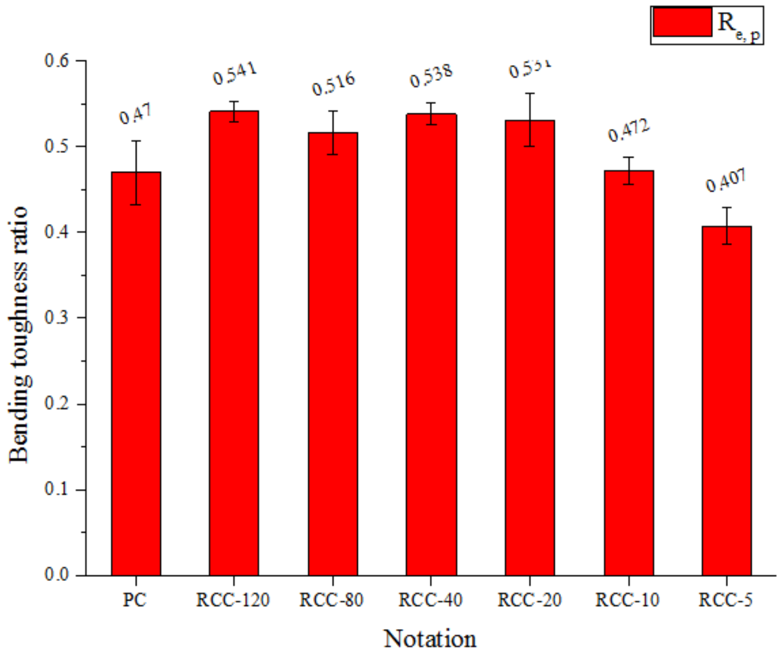
From the testing results, RC reduced the tensile properties of concrete. However, this kind of reduction was based on the loss of compressive strength. Comparing to the compressive strength of PC with same concrete usage, the loss of tensile strength had been shrunken. That meant if the RCC was on the same compressive strength with PC, the tensile properties could be better than the latter one.

(3) Flexural properties

As an important index of the internal structural properties of concrete, flexural toughness comprehensively summarizes the strength and deformation of concrete materials, and reflects the ability of concrete to resist vibration and impact load. Therefore, investigating the flexural toughness of rubber concrete can reflect the toughening effect of RCC.

The process of flexural - tensile test showed in Figure 5(a). Bending toughness ratio of PC and RCC were calculated and showed in Figure 5(a).

(a) Flexural - tensile test



(b) Bending toughness ratio

Figure 5. *Flexural properties of RCC.*

Although the addition of RC could not change the brittle cracking form of concrete like fiber agents, the bending toughness calculated from the load deflection curve showed that the fracture energy of RCC is greater than the ordinary concrete, which means better toughness and crack resistance.

However, the toughening effect of RC particles were not suitable for all sizes of rubber crumbs. The Figure 5 showed that rubber crumbs only with particle size less than 1.7 mm could be benefit to the toughness of concrete.

4. Durability

4.1. Impermeability

Impermeability of concrete refers to the ability to resist liquid and gas penetration. It is an important index of concrete. It is not only of great significance to structures requiring waterproof, but also to evaluate the ability of concrete to resist the invasion and corrosion of corrosive media in the environment. Impermeability is closely related to the compressive strength, crack resistance, shrinkage, frost resistance and corrosion resistance of concrete. This part of the paper mainly studies the ability of concrete to resist pressure water penetration, calculates the relative permeability coefficient by water penetration height method, and evaluates the impermeability of concrete. The fabrication of specimens and testing method were based on testing code for hydraulic concrete (SL/T 352-2020), each batch of concrete included six specimens. The section graphs of specimens after penetration test demonstrated in Figure 6 and test results listed in Table 5.

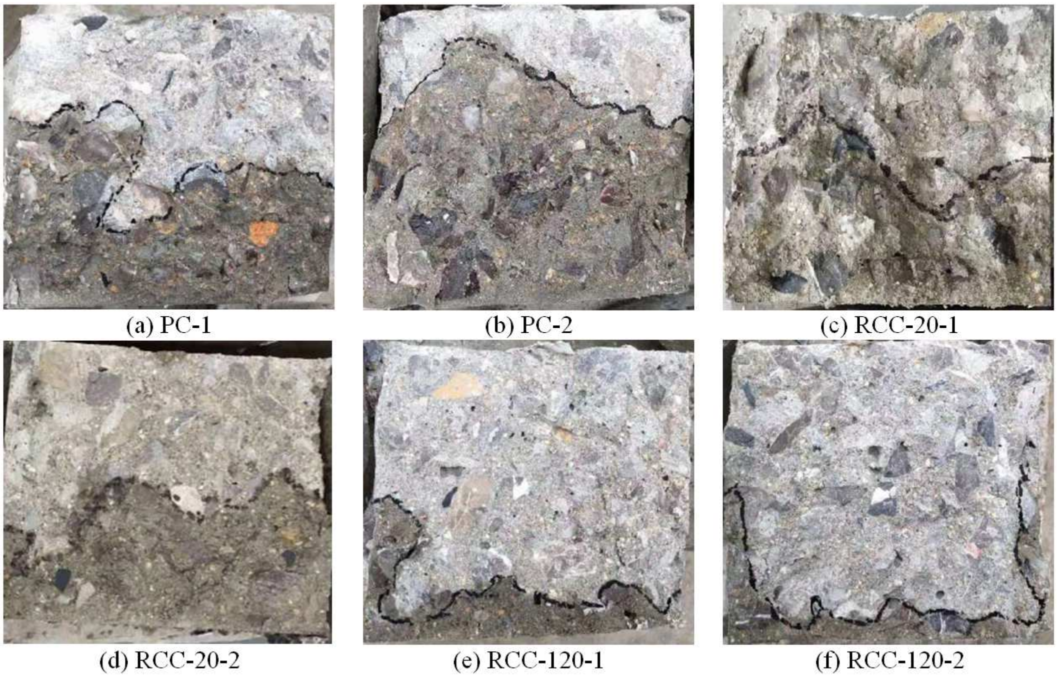


Figure 6. *Section graphs of specimens after penetration test.*

The osmotic pressure is set to 0.8 MPa and the osmotic pressure is maintained for 8 h, the average penetration height of PC was 8.52cm and relative permeability coefficient was 5.56×10^{-6} cm/h. The batch of RCC-20 and RCC-120, on the contrary, reduced 25.12% and 78.87% comparing to the PC. The results showed that adding rubber particles can effectively improve the impermeability of concrete. With the same dosage, the improvement effect of fine rubber particles is more obvious than that of adding coarse rubber particles.

Table 5. *Penetration test results of RCC.*

Notation	Penetration height	Relative permeability coefficient	Standard deviation
PC	8.52 cm	5.56×10^{-6} cm/h	0.58
RCC-20	6.38 cm	3.12×10^{-6} cm/h	0.52
RCC-120	1.80 cm	0.25×10^{-6} cm/h	0.34

Adding fine rubber particles can improve the impermeability of concrete for the following three reasons: First of all, the rubber particles could fill the harmful pores in the concrete so as to raise the concrete compactness and improve the impermeability. Secondly, rubber particles are hydrophobic polymer materials, a hydrophobic film can be formed on the surfaces to increase the seepage resistance of water and reduce the suction effect of pores. Finally, due to the air entrainment of rubber crumbs, a large number of micro-size bubbles increase the tortuosity of concrete internal structures and reduce the through cracks. On the other hand, the coarse rubber crumbs cannot bring the same effect of the fine ones. The surface roughness increased with the extend of particle size, which leads to the increase of porosity on the contact interface, and reduces the impermeability of RCC.

4.2. Freezing and Thawing Resistance

In this part, by calculating relative dynamic modulus of elasticity and DF value (Durability factor) of rubber concrete, the effect of rubber crumbs on the freezing and thawing resistance of concrete had been studied. The comparison of concrete specimens before and after freeze-thaw failure is shown in Figure 7.

Figure 7. *Appearance comparison of specimens before / after freeze-thaw test.*

Figure 8 shows the comparison of changes in relative dynamic modulus of elasticity between PC and RCC. Basically, with the running of freeze-thaw cycles test, the relative dynamic modulus of elasticity of concrete decreased. At the same number of freeze-thaw cycles, the descending order of relative dynamic modulus of elasticity was RCC-120, RCC-20 and PC. The relative dynamic modulus of elasticity of PC and RCC-20 slightly reduced after 25 and 50 freeze-thaw cycles, but sharply after 75 freeze-thaw cycles. After 150 cycles, the relative dynamic modulus of elasticity decreased to less than 60%. However, the relative dynamic modulus of elasticity of RCC-120 was no less than 60% after 200 freeze-thaw cycles.

DF value is the relative dynamic modulus of elasticity of the specimen after 300 freeze-thaw cycles. If the number of freeze-thaw cycles is less than 300, the relative dynamic elastic modulus is less than 60%, or the mass loss rate reaches 5%, the DF value could be calculated according to the following formula 2:

$$DF = \frac{P_N}{300} \times 100\% \quad (2)$$

Among the expression, P_N stood for the relative dynamic modulus of elasticity of concrete. The relative dynamic modulus of elasticity and DF value are listed in Figure 8.

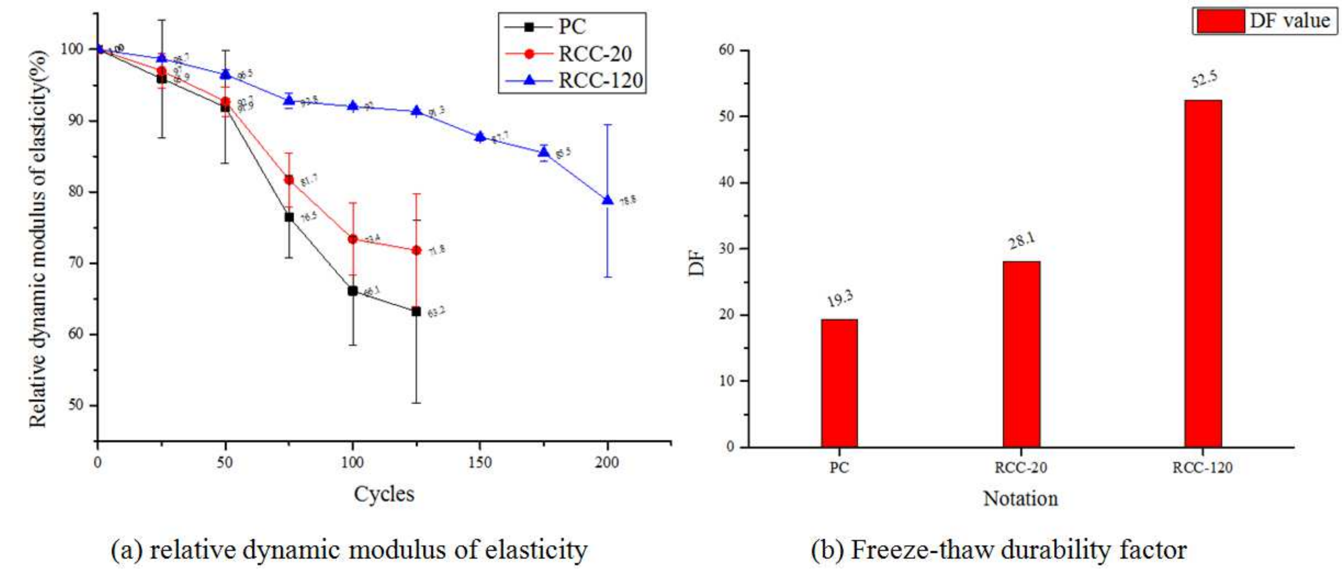
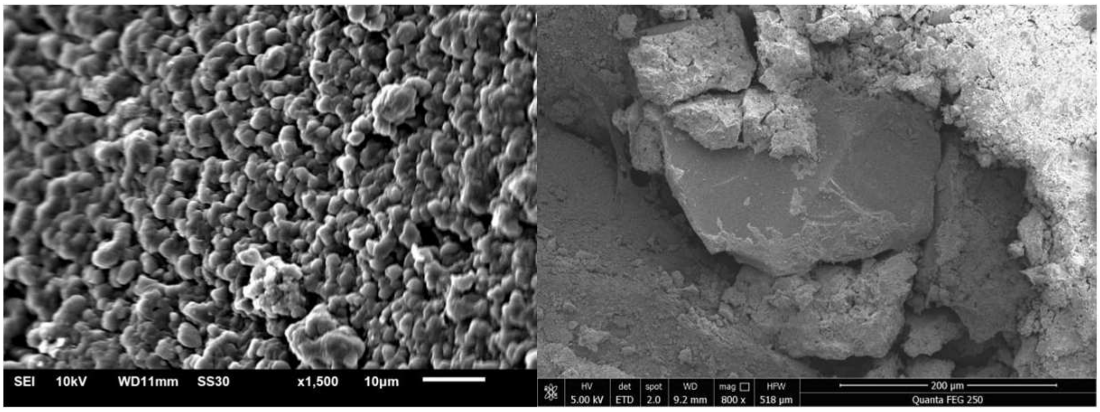


Figure 8. *Freezing and thawing resistance of concrete.*

So, adding rubber particles could improve the frost resistance of concrete, and under the same dosage of 10%, the improvement effect of fine rubber particles is significantly better than coarse ones. According to the previous research on workability, the air content of RCC-120 and RCC-20 were basically on the same level. However, there was a great difference in freezing-thawing resistance between them. The reason could be concluded as follows: The bubble diameter and spacing of RCC is determined by particle sizes of rubber crumbs and only the micro-sized bubbles with a reasonable spacing distribution benefit the freezing-thawing resistance of concrete.

5. Microstructure

In order to explain the lack of adhesion between rubber crumbs and cement paste, which usually occurred in RCC with the coarse rubber crumbs, we prepared a sample of RCC-10 and the rubber crumbs of 1.7mm. Figure 9 showed the micro morphology of the samples obtained under SEM.



(a) Surface of rubber crumb (×1500) (b) Microstructures of RCC (×800)

Figure 9. *SEM images of rubber crumb and interface between rubber and hydrations.*

As shown in Figure 9(a), due to the surface tension and roughness of the surface of rubber crumbs, water cannot soak into the interface zone between rubber and hydrations. In that way, the degree of cement hydration is declined in this area, which led to poor adhesion of rubber and cement.

Hardened cement paste is a complex multi-phase system and pore structure is closely related to the properties of concrete. In this paper, samples which prepared of RCC-120, RCC-40 and RCC-10 are taken to get pore structures with MIP test. The porosity, total pore volume, total pore area, average pore diameter, median pore diameter and most probable aperture of the sample are shown in Table 6.

Table 6. *Testing results of MIP.*

Notation	Porosity	Total pore volume	Total pore area	Average pore diameter	Median pore diameter	Most probable aperture
PC	9.6%	0.047 mL/g	4.351 m^2/g	43.2 nm	108.5 nm	151.4 nm
RCC-120	10.9%	0.054 mL/g	7.297 m^2/g	29.6 nm	84.6 nm	121.0 nm
RCC-40	9.9%	0.050 mL/g	4.270 m^2/g	46.8 nm	117.0 nm	151.1 nm
RCC-10	14.5%	0.049 mL/g	4.479 m^2/g	43.8 nm	113.3 nm	121.0 nm

The MIP test result proofed the excellent durability and mechanical properties of RCC-120 was based on the optimization of internal pore structure of concrete by fine rubber crumbs. Figure 10 demonstrated the proportion of different pore diameter ranges of samples.

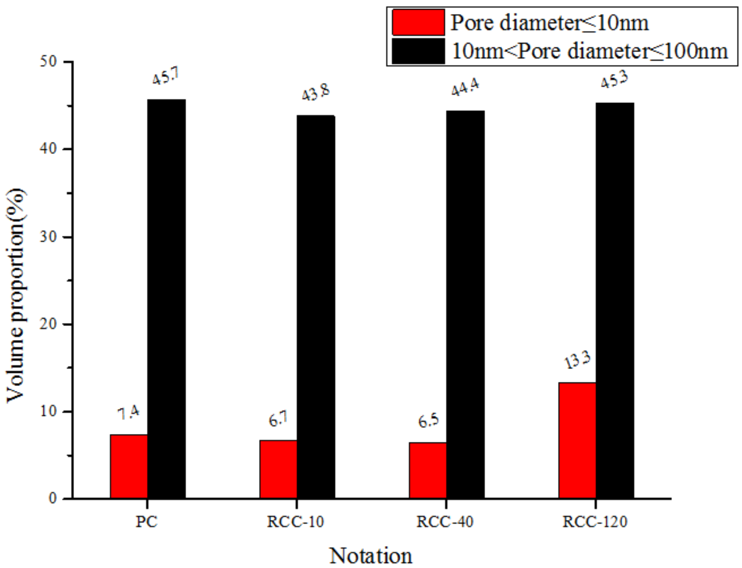


Figure 10. *Proportion of different pore diameter ranges in samples.*

What we can draw from the distribution of different pore diameter is that the RCC-120 got the most pores of diameter less than 100nm. Such pores are called cementitious pores in concrete, could increase the durability without harming the mechanical properties [14].

6. Conclusion

(1) The compressive strength of concrete can be reduced by adding rubber crumbs. However, there is no nonlinear relationship between the strength and the particle size of rubber powder.
(2) Fine rubber crumbs could raise the durability of concrete, especially on freezing-thawing resistance and impermeability.
(3) The main reason for the distinction of properties between PC and RCC is the different distribution of pore diameters.

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