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Effect of rubber particles on properties and frost resistance of self-compacting concrete

Miao Liu [1a], Jianhua Xiao[*1], En Yang [2] and Lijuan Su [1c]

[1] *Liaoning Technical University, Xihe District, Fuxin City, Liaoning 123000, China*
[2] *Pengshui Miao and Tujia Autonomous County Housing and Urban-Rural Development Committee, Chongqing 409614, China*

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Abstract. In order to study the effect of rubber particle size and admixture on the frost resistance of self-compacting concrete, three self-compacting concrete specimens with equal volume replacement of fine aggregate by rubber particles of different particle sizes were prepared, while conventional self-compacting concrete was made as a comparison specimen. The degradation law of rubber aggregate self-compacted concrete under freeze-thaw cycles was investigated by fast-freezing method test. The results show that the rubber aggregate has some influence on the mechanical properties and freeze-thaw durability of the self-compacting concrete. With the increase of rubber aggregate, the compressive strength of self-compacting concrete gradually decreases, and the smaller the rubber aggregate particle size is, the smaller the effect on the compressive strength of the matrix; rubber aggregate can improve the frost resistance of self-compacting concrete, and the smaller the rubber particle size is, the more obvious the effect on the improvement of the frost resistance of the matrix under the same dosage. Through the research of this paper, it is recommended to use 60~80 purpose rubber aggregate and the substitution rate of 10% is chosen as the best effect.

Keywords: freeze-thaw damage; relative dynamic modulus of elasticity; rubber aggregate; self-compacting concrete

0. Quotes

Rubber waste is an inert polymer material, which is not easily degraded under natural conditions, so how to use these black solid waste rationally has become the focus of attention of scholars at home and abroad (Youssf et al. 2016, Han et al. 2016, Thomas et al. 2016 and Li et al. 2019). The emergence of rubber aggregate concrete provides a new way for the resource utilization of waste rubber building materials, and the crushed rubber in the form of aggregate can improve the performance of concrete (Wang et al. 2017, Kelechi et al. 2022 and Youssf et al. 2017). Mishra and Panda (2015) and Bompa *et al*. (2017) studied the intrinsic structure relationship of rubber aggregate concrete. Yang *et al*. (2019) and Zhang *et al*. (2021) studied the impact resistance of rubber aggregate on concrete. Werdine *et al*. (2021) and Salhi *et al*. (2019) investigated the effect of rubber aggregate on the durability performance of reinforced concrete members under chloride salt attack environment. The small density of rubber aggregate tends to float during the concrete vibrating process, which causes uneven distribution of rubber aggregate and affects the performance of the matrix. Self-compacting concrete can greatly avoid the floating phenomenon of light aggregate. Güneyisi (2010) studied the working performance of rubber aggregate self-compacting concrete in fresh state. Qiang *et al*. (2017) investigated the damage principal relationship and resistance to sulfate corrosion of rubber aggregate self-compacting concrete. Freeze-thaw damage is the biggest problem of concrete durability in the “Three Norths” (Northeast, Northwest and North China) of China. To promote the use of rubber-aggregate self-consolidated concrete in cold regions, it is necessary to investigate its durability under freeze-thaw conditions, and there is still a lack of research on the freeze-thaw damage performance of rubber-aggregate self-consolidated concrete.

In this paper, the frost resistance of self-compacting concrete with rubber aggregate of different particle sizes and admixtures was investigated experimentally. On the basis of the analysis of the effects of the rubber aggregate admixture and particle size on the workability and compressive strength of the self-compacting concrete, the effects of the rubber aggregate particle size and admixture on the frost resistance and durability of the self-compacting concrete were investigated by comparing the changes of the relative dynamic elastic modulus of each group of specimens under the action of freeze-thaw cycles through the rapid freeze-thaw cycles.

*Corresponding author, Ph.D.,
E-mail: xjhua55@163.com
[a] Ph.D., E-mail: 65842239@qq.com

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(a) 0.15~0.25 mm particle size (b) 0.38~0.55 mm particle size (c) 1~3 mm particle size

Fig. 1 Rubber powder (particles) of different particle sizes

Table 1 Relevant technical indicators of cement

Indicators grade	Specific surface area /m^2 /kg	Density /kg/m^3	CaO /%	MgO /%	SO_3 /%	C_3A /%	Burning loss /%	Chloride ion /%	Alkali content /%
42.5	343	3140	0.83	2.85	2.75	4.33	2.79	0.016	0.49

Table 2 Mechanical strength of cement

Cement grade	Compressive strength (MPa)		Flexural strength (MPa)	
	3d	28d	3d	28d
P.O42.5	27.9	51.8	6.23	9.6

1. Test

1.1 Raw materials and matching ratio

The rubber granules (RP) were produced and supplied by Tianjin Zhixin Company, and the rubber aggregates were 60~80 mesh (particle size 0.15~0.25 mm), 30~40 mesh (particle size 0.38~0.55 mm) and 7~15 mesh (particle size 1~3 mm), respectively, and the rubber granules used for the test are shown in Fig. 1. The cement was 42.5 grade Da Ying ordinary silicate cement produced in Fuxin City, Liaoning Province, with an apparent density of 3.14 g/cm^3. The fly ash was Grade I fly ash provided by Fuxin Power Plant, Liaoning Province, with a density of 2.7 and a burning loss of 1.8%. The chemical composition and mechanical index of cement are shown in Tables 1 and 2. The sand is ordinary river sand from Fuxin City, Liaoning Province, which belongs to Zone II, with fineness modulus of 2.62 and apparent density of 2.56 g/cm^3 ; the stone is natural gravel with particle size of 5~16 mm and apparent density of 2.70 g/cm^3 ; the water reducing agent is polycarboxylic acid high efficiency water reducing agent; the mixing water is tap water; the concrete ratio is shown in Table 3.The rubber aggregate was replaced by 0, 5%, 10% and 15% of fine aggregate (volume replacement rate).

Table 3 Rubber aggregate self-compacting concrete mix ratio (kg/m^3)

Types	Cement	Fly ash	Sand	Gravel	Water	Rubber	SP
SCC	365	176	758	866	180	0	8.11
SCCR1-5	365	176	721	866	180	12.9	8.11
SCCR1-10	365	176	683	866	180	25.9	8.11
SCCR1-15	365	176	645	866	180	38.8	8.11
SCCR2-5	365	176	721	866	180	14.3	8.11
SCCR2-10	365	176	683	866	180	28.5	8.11
SCCR2-15	365	176	645	866	180	42.8	8.11
SCCR3-5	365	176	721	866	180	18.2	8.11
SCCR3-10	365	176	683	866	180	36.4	8.11
SCCR3-15	365	176	645	866	180	54.5	8.11

*Notes: SCC means self-compacting concrete. In SCCRx-m, SCCR means the self-compacting concrete with crumb rubber, x means the particle size of the crumb In SCCRx-m, SCCR means the self-compacting concrete with crumb rubber, x means the particle size of the crumb rubber (1-0.15~0.25 mm; 2-0.38~0.55 mm; 3-1~3 mm), m means the replacement ratio of the crumb rubber (5-5%; 10-10%; 15-15%). SP means the super plasticizer.

1.2 Methods

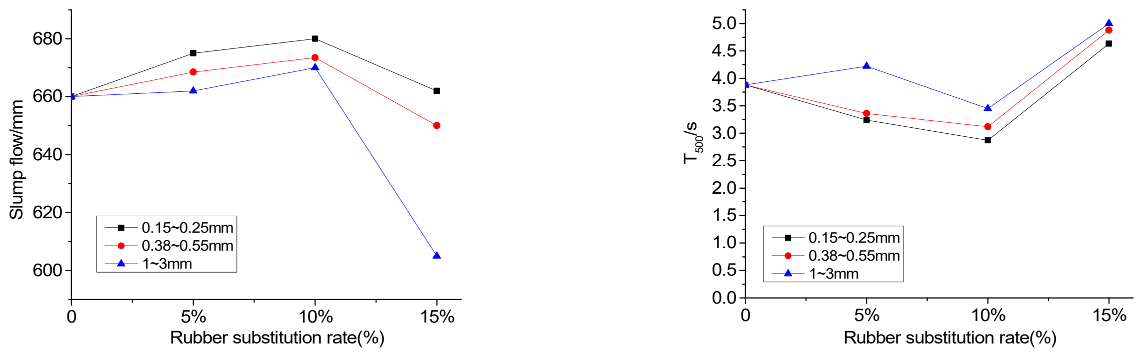
After the concrete was mixed, its slump increase, T_{500} The workability parameters such as flow time, J-ring expansion difference, and height difference between inside and outside of J-ring were tested. The stress-strain curves under pressure were measured by using the microcomputer-controlled electro-hydraulic servo universal testing machine of Liaoning University of Engineering and Technology. The rapid freeze-thaw cycle test was carried out on each group of self-compacting concrete specimens with reference to the recommended “Standard for Long-term Performance and Durability Test Methods of Ordinary Concrete” (GB/T50082), with a cycle time of 2-4 h. The test was stopped when the relative dynamic elastic modulus of the specimens was less than 60% or the mass loss exceeded 5%. The mass of the specimens was determined by a high-precision mass sensor, and the dynamic elastic modulus of the specimens was determined by a resonant dynamic elastic modulus tester.

2. Results and discussion

2.1 Workability and uniformity

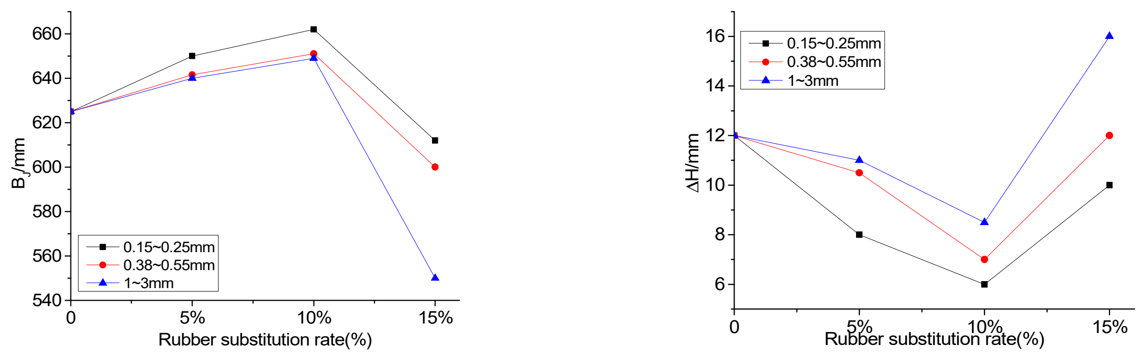
The results of the effect of rubber particle substitution on the workability of self-compacting concrete mixes are shown in Fig. 2. From Fig. 2(a), it can be seen that when the rubber particle size is constant, the rubber substitution rate increases, and the slump of self-compacting concrete increases first and then decreases. The maximum value appears when the rubber substitution rate is 10%. The slump increase increases for rubber particle size 0.15-0.25 mm 3.0%; The rubber particle size is 0.38~0.55 mm, the increase is 2.1%; The rubber particle size is 1~3 mm, the increase is 1.5%. When the rubber replacement rate is 15%, the slump increases of 0.38~0.55 mm and 1~3 mm is lower than that of the benchmark self-compacting concrete, which is 1.5% and 8.3% respectively. Except for the slump increase of 605 mm for rubber particle size of 1~3 mm, which does not meet the SF index of ballastless track filling layer, all other particle sizes can meet the requirements.

From Fig. 2(b), it can be seen that when the rubber particle size is certain, with the increase of rubber substitution rate, T500 flow time shows a trend of decreasing and then increasing. The lowest value appears when the rubber substitution rate is 10%, which coincides with the trend of slump extension. Among them, when the rubber substitution rate is 10%, the T500 flow time decreases by 26% when the rubber particle size is 0.15~0.25 mm. 25.7% when the rubber particle size is 0.38~0.55 mm. 11% when the rubber particle size is 1~3 mm. When the rubber substitution rate was 15%, the flow time of T500 was greater than that of the base concrete, which increased by 19.3%, 25.8% and 44.6%, respectively.



(a) Slump increase (b) T_{500} flow time

Fig. 2 Effect of rubber substitution rate on slump increase and T_{500} flow time of self-compacting concrete



(a) J-ring slump extension (b) Height difference between inside and outside of J-ring

Fig. 3 Effect of rubber substitution rate on J-ring slump increase and internal and external height difference of self-compacting concrete

The J-ring slump increase is shown in Fig. 3(a), with the increase of rubber substitution rate, the J-ring slump increase shows a trend of first increasing and then decreasing, the maximum value appears when the rubber substitution rate is 10%. When the rubber substitution rate is 15%, the J-ring slump increase decreases significantly. The height difference between the inside and outside of the J-ring ($\Delta H = h_1 - h_2$) is shown in Fig. 3(b), with the increase of rubber substitution rate shows a trend of first decreasing and then increasing. When the rubber substitution rate is 15%, the height difference rises and the gap passage rate is lower. It indicates that the appropriate amount of rubber incorporation will enhance the self-compacting fluidity and steel gap passage rate.

The above experimental results show that the mixing of the appropriate amount of fine rubber powder will improve the fluidity of self-compacting concrete. The rubber substitution rate of more than 10% will reduce its fluidity, the trend of self-compacting slump expansion and T500 flow time coincides. The slump increase is large, then T500 flow time is short. The reason is that the smaller the rubber particle size, the stronger the air-entraining properties, effectively reducing the friction between materials. But the rubber is excessive, its specific surface area increases, the water demand increases, and the mix fluidity will become poor; on the other hand, self-compacting concrete is affected by the replacement of water in the voids between materials by fly ash, reducing the relative sliding resistance between materials, and its fluidity improves.

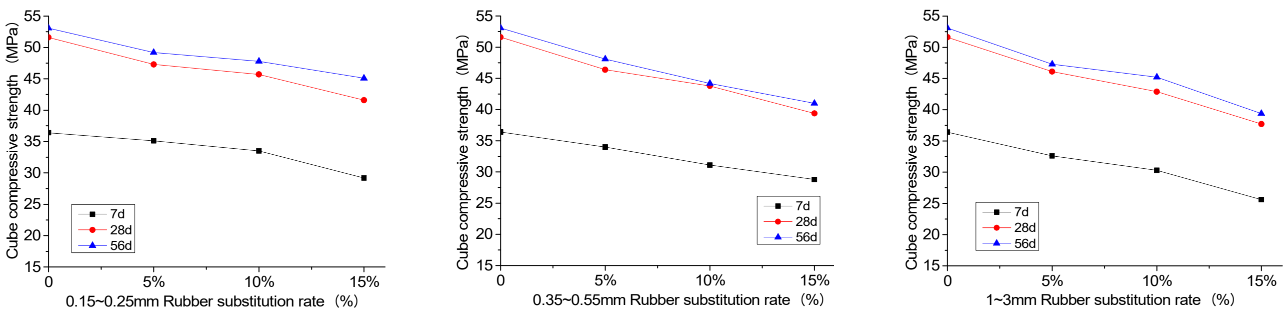
In the concrete mix proportion, the concrete fluidity research of rubber powder replacing sand is considered alone, so the experimental results are more intuitive. If the engineering application is considered, on this basis, the slump will be better by adjusting the dosage of water reducing agent and water to meet the engineering requirements.

2.2 Mechanical properties

(1) The effects of rubber substitution rate on the compressive strength and stress-strain curves of self-compacting concrete cubes are shown in Fig. 4. The decreases were 7.3%, 11.4%, and 19.4% at the curing age of 28 d and 7.4%, 9.8%, and 17.2% at the curing age of 56 d, respectively.
In summary, the mixing of rubber powder (particles) in the self-compacting concrete to replace a certain amount of fine aggregate river sand reduces the compressive strength of self-compacting concrete, and the higher the replacement rate, the more obvious the decreasing trend of the compressive strength of rubber self-compacting concrete, but at the replacement rate of 10% is a watershed, the compressive strength of specimens with equal volume replacement of fine aggregate within 10% decreases more slowly, and when the replacement rate When the substitution rate reaches 15%, the decline rate increases sharply. This is because the appropriate amount of rubber can play a filling role inside the self-compacting concrete, but rubber is an elastomer, cannot play a skeletal role in the concrete.

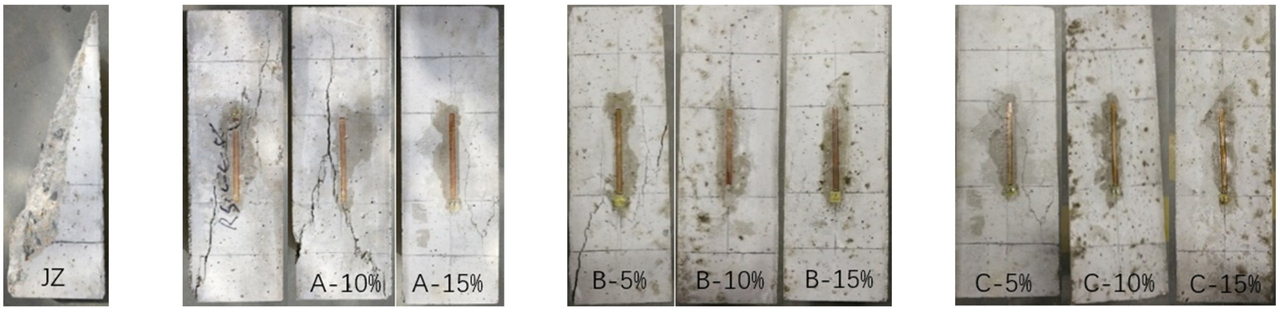
(2) From Fig. 4, it can also be seen that the size of rubber particle size affects the change of cube compressive strength. Under the same substitution rate, rubber with different particle sizes will reduce the strength grade of self-compacting concrete, and the smaller the size of the mixture, the smaller the decrease of cube compressive strength of self-compacting concrete. When the rubber substitution rate is 10% and 15%, the cube compressive strength of 1~3 mm self-compacting concrete decreases most significantly. This is because the smaller the particle size of rubber powder in the same volume, it can play the role of filling the internal pore structure of concrete, and then enhance the denseness of self-compacting concrete, while the elastic space of rubber powder is much lower than that of rubber grains, which can keep in line with the low deformation capacity of concrete and delay the premature cracks due to inconsistent deformation.

(3) The specimens were subjected to uniaxial compression test, and the damage pattern of the specimens is shown in Fig. 5. The cracks of the benchmark self-compacting concrete appeared soon after compression, and the cracks spread rapidly and interconnected until brittle damage, and the surface concrete spalled and disintegrated immediately; the speed of cracking of the rubber self-compacting concrete after compression was slower than that of ordinary concrete, and a certain yielding phenomenon appeared, and there was slight



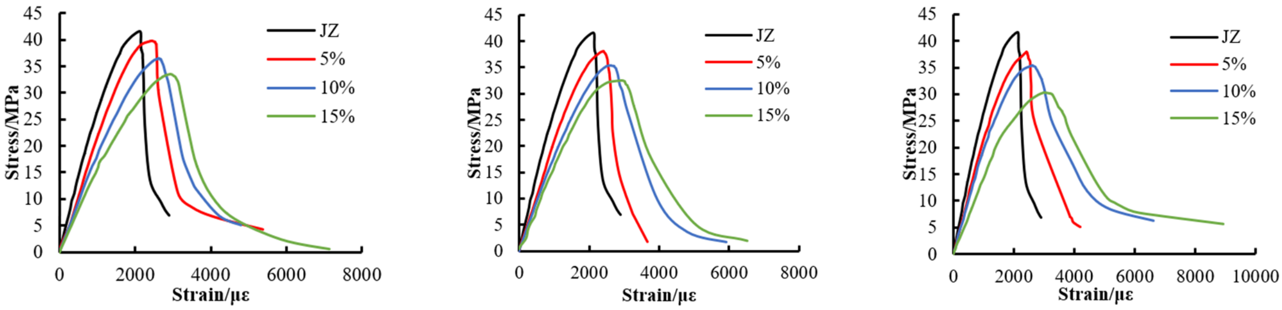
(a) 0.15~0.25 mm (b) 0.38~0.55 mm (c) 1~3 mm

Fig. 4 Effect of rubber substitution rate on the compressive strength of self-compacting concrete cubes



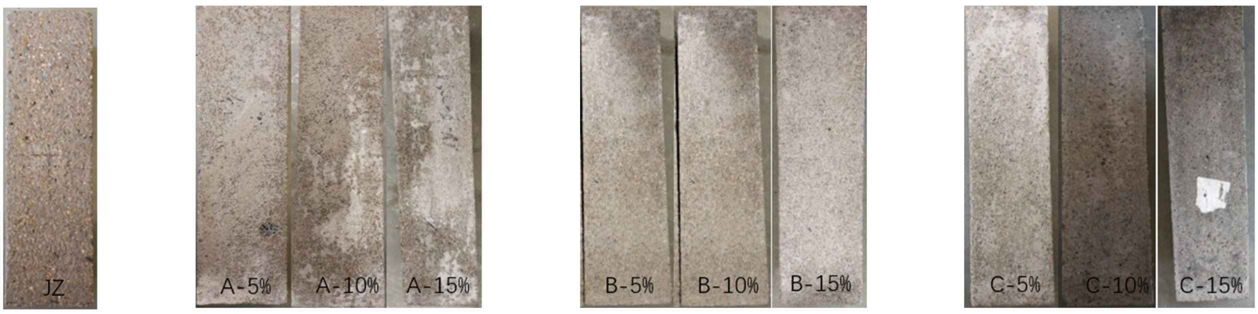
(a) JZ (b) 0.15~0.25 mm (c) 0.38~0.55 mm (d) 1~3 mm

Fig. 5 Axial compression damage of rubber self-compacting concrete



(a) 0.15~0.25 mm (b) 0.38~0.55 mm (c) 1~3 mm

Fig. 6 Effect of rubber substitution rate on stress-strain curve of self-compacting concrete



(a) JZ (b) 0.15~0.25 mm (c) 0.38~0.55 mm (d) 1~3 mm

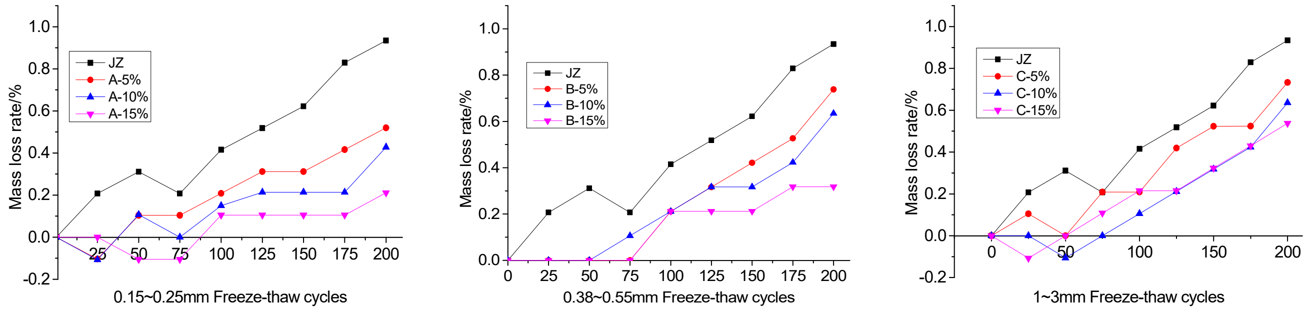
Fig. 7 Appearance damage of rubber self-compacting concrete after 200 freeze-thaw cycles

deformation in the early stage of compression. After cracking, the crack diffusion linkage is slower and less cracks are produced. Damage to the surface of the concrete rarely produce the phenomenon of shedding, after unloading part of the cracks have a tendency to close. Since the rubber played a role in inhibiting and slowing down the development of cracks inside the self-compacting concrete, the incorporation of rubber greatly improved the brittle damage morphology of self-compacting concrete and improved its ability to adapt to deformation.

(4) The stress-strain test results of self-compacting concrete are shown in Fig. 6. As the rubber replacement rate increases, the area enclosed by the peak curve and the horizontal coordinate (peak integral area) of self-compacting concrete becomes larger, which indicates that the ability of self-compacting concrete column to absorb and store the energy of the applied load increases with the increase of the replacement rate. Since the rubber itself has the deformation ability, the incorporation of rubber gives the self-compacting concrete a plastic characteristic, the more significant with the increase of the rubber substitution rate, which enhances the toughness of the self-compacting concrete.

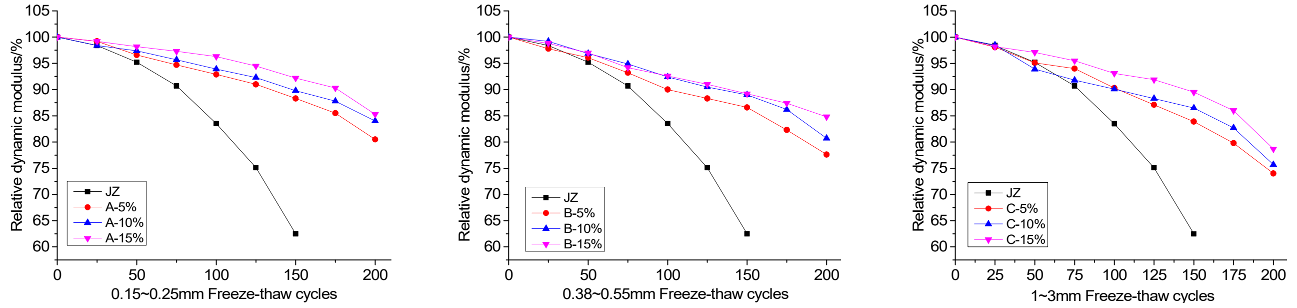
2.3 Durable performance

Under the action of freeze-thaw cycles of rubber self-compacting concrete, the specimen appearance will be changed continuously with the increase of the number of freeze-thaw cycles, and the degree of damage to the specimen appearance of the comparison specimen can, to



(a) 0.15~0.25 mm (b) 0.38~0.55 mm (c) 1~3 mm

Fig. 8 Effect of rubber substitution rate on mass loss rate of self-compacting concrete under freeze-thaw cycles



(a) 0.15~0.25 mm (b) 0.38~0.55 mm (c) 1~3 mm

Fig. 9 Effect of rubber substitution rate on the relative dynamic modulus of elasticity of self-compacting concrete under freeze-thaw cycles

a certain extent, explain the freezing resistance of the specimen. The appearance of the specimens after 200 freeze-thaw cycles for the base self-compacting concrete and rubber self-compacting concrete specimens is shown in Fig. 7.

According to the observation during the test, the appearance of each group of specimens can be understood. When freeze-thaw cycles were not conducted, the surface of the self-compacting concrete specimens was flat, and with the increase of the number of freeze-thaw cycles, the internal deterioration cracks of the benchmark concrete specimens not mixed with rubber increased, the cement smear gradually peeled off, and the coarse and fine aggregates were exposed. With the peeling of the smear, the black rubber powder (particles) and fine aggregates were exposed, and it was found that the higher the replacement rate of rubber powder (particles), the less the smear and aggregates were peeled off under the same number of freeze-thaw cycles; and the larger the rubber particle size, the worse the smear was peeled off. It can be concluded from the observation of the development of the apparent state of the specimens that the rubber with particle size of 0.15-0.25 mm and substitution rate of 15% can improve the frost resistance of the self-compacting concrete in the test.

As analyzed in Fig. 8, the mass loss of self-compacting concrete becomes smaller and smaller as the rubber substitution rate increases from 0 to 15% with the incorporation of rubber powder (particles) of the same particle size. After 200 freeze-thaw cycles, the mass loss rate of the baseline self-compacting concrete reached 0.9%, which was higher than that of all self-compacting concretes incorporated with rubber powder, and 4.4 times higher than that of the specimen with the lowest mass loss rate (1-3 mm particle size and 15% substitution rate); the highest mass loss rate was for the self-compacting concrete incorporated with 1~3 mm particle size and 5% substitution rate, and the baseline self-compacting concrete was 1.27 times. The freeze-thaw effect of self-compacting concrete mixed with rubber powder (granules) is significantly better than that of the reference self-compacting concrete and meets the requirement of frost resistance.

The concrete specimens with higher rubber content were mixed with more bubbles during the mixing. At the beginning of the freeze-thaw cycle, the surface of the specimen was cracked and damaged due to the freeze-thaw of the concrete, and the water entered the bubbles, making the quality of the specimen rise. However, the quality of this part of water remained basically constant, and with the continuous freeze-thaw cycle, the surface quality loss of the concrete was increasing, and the quality of the specimen began to decline.

In the whole test process, the relative dynamic elastic modulus of the specimens changed as shown in Fig. 9, with the increase of the number of freeze-thaw cycles, the relative dynamic elastic modulus of the self-compacting concrete specimens showed a decreasing trend, and the decreasing trend in the early stage was relatively gentle, but the decreasing trend in the later stage was obvious; under the same number of freeze-thaw cycles, when the rubber particle size was the same, the higher the rubber substitution rate, the greater the relative dynamic elastic modulus of the specimens.

When the number of freeze-thaw cycles reached 200 and the rubber substitution rate increased from 5% to 15%, the relative dynamic elastic modulus of self-compacting concrete was 80.5%, 84% and 85.3% when the rubber particle size was 0.15~0.25 mm; the relative dynamic elastic modulus of self-compacting concrete was 77.6%, 80.7% and 82.2% when the rubber particle size was 0.38~0.55 mm; the relative dynamic elastic modulus of self-compacting concrete was 74%, 75.7% and 78.7% when the rubber particle size was 1~3 mm. 80.7%, 82.2%; when the rubber particle size is 1~3 mm, the relative dynamic elastic modulus of self-compacting concrete is 74%, 75.7%, 78.7% respectively. The variation of relative dynamic elastic modulus of self-compacting concrete specimens with $E_R^{5\%} < E_R^{10\%} < E_R^{15\%}$. The incorporation of rubber significantly improved the dynamic elastic modulus of self-compacting concrete and improved the frost resistance of self-compacting concrete.

In conclusion, the reason why rubber can improve the frost resistance of self-compacting concrete is that rubber, as an elastic material, can absorb the strain energy generated by self-compacting concrete in the process of bearing the load, including the pressure caused by water freezing; on the other hand, rubber as a substitute for fine aggregate, the finer the rubber particle size, the better it can play the role of filling dense, reducing the water inside the self-compacting concrete. On the other hand, rubber as a substitute for fine aggregate, the finer the rubber particle size, the better it can play the role of filling dense, reduce the water content inside the self-compacting concrete, effectively prevent the specimen from cracking due to the expansion of pore water icing, thus its anti-freezing performance is improved; in addition, the admixture of rubber will introduce more air bubbles, play a certain buffering effect on the expansion of water icing, delay the development of cracks, and the smaller the particle size, the larger the specific surface area, the more obvious the effect. In addition, the smaller the particle size of coarse aggregate used in self-compacting concrete, the higher its air content; self-compacting concrete does not need to be pounded when it is placed, and the internal denseness is better, which also improves its frost resistance to a certain extent.

3. Conclusions

The recycling of waste is widely recognized as the prevailing trend and future direction in global waste management. Utilizing rubber as an aggregate in self-compacting concrete presents a viable solution for reusing solid waste. This study conducts experimental research on rubber granule self-compacting concrete, focusing on its workability, mechanical properties, and frost resistance, with the aim of promoting the application of rubber self-compacting concrete in cold regions. The main findings of the paper are as follows:

- When the rubber particles replace not more than 10% of the fine aggregate by the same volume, the slump increase of freshly mixed self-compacting concrete increases as the amount of rubber particles increases. T_{500} and B_J (2) The slump increases of freshly mixed self-compacting concrete increases and decreases with the increase of rubber particles. The rubber particles are evenly distributed in the hardened self-compacting concrete.
- After the replacement amount of rubber particles is greater than 10%, the incorporation of rubber particles significantly reduces the compressive strength of self-compacting concrete, but increases the peak strain of concrete and improves the toughness of self-compacting concrete.
- The incorporation of rubber particles can improve the dynamic elastic modulus of concrete during the freeze-thaw cycle, and at the same time can make the concrete resistant to sulfate dry and wet cycles without significant reduction in performance.

Through the analysis of test results, it is evident that rubber particles will introduce air bubbles into the concrete, thereby impacting its properties and frost resistance. In future studies, micro-observation tests can be incorporated to analyze the freeze-thaw damage mechanism of rubber granular concrete. Additionally, the interfacial state of rubber particles in concrete can be adjusted using multi-blending technology to enhance its frost resistance.

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