Feng *et al. Int J Concr Struct Mater (2021) 15:37*
https://doi.org/10.1186/s40069-021-00475-8

International Journal of Concrete Structures and Materials

RESEARCH **Open Access**

Effect of Waste Tire Rubber Particles on Concrete Abrasion Resistance Under High-Speed Water Flow

Ling-Yun Feng*, Ai-Jiu Chen and Han-Dong Liu

Abstract

Rubberized concrete is an environmentally friendly building material that mixes rubber particles from old automobile tires into normal concrete in place of fine aggregate. The addition of rubber particles can improve the abrasion resistance of normal concrete observably. It has a good application prospect in hydraulic engineering, especially in the concrete building parts with high abrasion resistance. However, there are few experimental studies on the abrasion resistance of rubberized concrete, and the influence law and mechanism of rubber particles on the abrasion resistance of concrete are not understood. In this paper, the abrasion resistance of rubberized concrete is studied using the underwater-steel-ball method. The results show that rubber particles increase the slump of concrete mixtures. The abrasion resistance of rubberized concrete increases significantly with increasing rubber particle content, whereas the compressive strength decreases linearly. For the same rubber particle size and content, the abrasion resistance of rubberized concrete positively correlates with compressive strength and larger rubber particles significantly improve the abrasion resistance. Rubber particle content is the factor that most strongly affects abrasion resistance of rubberized concrete, followed by the compressive strength. Rubber particle pretreatment methods of NaOH + KH570 can significantly improve the abrasion resistance of rubberized concrete.

Keywords: Rubberized concrete, Rubber particles, Abrasion resistance, High-velocity flow, Compressive strength

1 Introduction

The storage of water in dams can provide sustainable water resources for people's production and life, and also reduce the harm of floods (Basheer, 2021; Yang et al., 2021). With the improvement of dam construction technology, the height of dam construction is also increasing. In China, more than 200 dams are over 100 m high, including the world's highest arch dam, which is 305 m high (Tan et al., 2021). The construction of high dam puts forward higher requirements for the abrasion resistance of concrete. Even at low dam, the high content of sand and gravel in flood discharge can cause serious damage to concrete structures. Therefore, how to improve the abrasion resistance of concrete has always been the research focus of hydraulic researchers.

The mixing of rubber particles (RPs) from crushed automobile tires into normal concrete (NC), in place of a fine aggregate (sand), offers not only way to recycle and alleviate the environmental harm associated with automobile tire waste (Elom, 2012; Pavlinek et al., 2009), but also improves the engineering properties of NC, including shock resistance (Aliabdo et al., 2015), fatigue resistance (Liu et al., 2013; Zhang & Zhao, 2015), corrosion resistance (Gupta et al., 2016; Thomas et al., 2016a, 2016b; Zhu et al., 2020), frost resistance (Zhu et al., 2018), and abrasion resistance (2016a; b; Bisht & Ramana, 2017; Gupta et al., 2014; Kang & Fan, 2011; Segre & Joekes, 2000; Sukontasukkul & Chaikaew, 2006; Thomas et al., 2014; Xie & Lou, 2014; Zhang & Li, 2012),

*Correspondence: 405759200@qq.com
North China University of Water Resources and Electric Power, Zhengzhou 450046, China
Journal information: ISSN1976-0485 / eISSN 2234-1315

and has thus attracted extensive research attention. Eldin and Senouci (1993, 1994) first studied the mixing of RPs into NC and adopted the term rubberized concrete (RC). Their work showed that the partial replacement of RPs in the aggregate causes the concrete failure mode to change from brittle failure to ductile and plastic failure, and increases its ability to absorb a large amount of plastic energy under compression and tensile loads. Ho et al. (2011)performed three-point bending tests on notched beams and showed that the brittleness index and damage of concrete decrease with increasing RP content and that the RP content can reach 40%. Al-Tayeb et al. (2012) also performed three-point bending tests and showed that the RPs improves the fracture properties of concrete and that the RP content can reach 20%.

Mendis et al. (2017) studied the influence of RPs on the stress–strain relationship of concrete and showed that the elastic modulus of concrete decreases with increasing RP content and the peak and ultimate strains increase, indicating an improvement of the deformation performance of concrete, similar to other studies (Aslani, 2016; Gupta et al., 2016; Li et al., 2018). Taha et al. (2008) reported that the impact resistance of concrete increases with increasing RP content and a maximum replacement level of 50%. Atahan and Yücel (2012) found that the energy absorption of concrete under dynamic impact loading increases with increasing RP content for replacement levels of < 80% RP content by aggregate volume, but did not increase further upon the addition higher RP content. Aliabdo et al. (2015) reported that visible cracks and the number of strikes leading to concrete damage under repeated impact loading increased with increasing RP content.

Although RPs in concrete reduce brittleness, increase plasticity, and improve the deformation performance of concrete, they also significantly reduce the concrete strength (Gregori et al., 2019; Hadzima-Nyarko et al., 2019; Huang et al., 2020; Williams & Partheeban, 2018). The RPs are made from automobile tires and their surfaces are thus rich in carbon powder and zinc stearate, which are necessary additives in automobile tire production. These additives cause RPs to be strongly hydrophobic, which results in a poor bonding quality between the RPs and cement stone, increases the number of pores, and reduces the strength of concrete. With increasing RP content, the reduction of the concrete-bearing capacity is often greater than the increase of deformation capacity, which limits the application of RC in concrete engineering. Although numerous studies (Khern et al., 2020; Liu et al., 2016; Segre et al., 2002; Youssf et al., 2016) have proposed the modification of RPs using water washing or alkaline solution or organic solvent treatments, the hydrolyzed zinc stearate on the RPs surface increases the adhesion between RPs and cement matrix and reduces the reduction range of the concrete strength to a certain extent, thus limiting the pretreatment effect.

Thomas et al., (2016a, 2016b) studied the influence of RPs on the chloride erosion resistance of concrete and showed that for 2.5–7.5% RP content, the chloride penetration depth is less than or equal to that of the reference concrete without RPs. Similar results were obtained in experimental studies by Zhu et al. (2020) and Zhu et al. (2018).

Savas et al. (1997) found that the durability coefficient of RC at 300 freeze–thaw cycles was 60% higher than that of NC when the RPs were mixed at 10% and 15% of the cement weight; however, the durability did not meet the American Society for Testing and Materials standard requirements when the dosage was 20% or 30%. Paine et al. (2002) showed that the incorporation of smaller RPs greatly improves the frost resistance of concrete, compared with larger RPs, to an equivalent extent as the incorporation of air entraining admixture.

The influence of RPs on the abrasion resistance of concrete used in road engineering has been extensively studied. Thomas et al., (2016a, 2016b) applied a 600-N load on a 100 × 100 × 100 mm cubic RC specimen and performed grinding tests on the specimen surface. Their results show that the abrasion depth of concrete decreases with increasing RP content. Similar results were reported by Bisht and Ramana (2017), Zhang and Li (2012), and Sukontasukkul and Chaikaew (2006). However, few experimental studies have addressed the influence of RPs on the abrasion resistance of concrete used in hydraulic engineering. The abrasion resistance of concrete used in hydraulic engineering reflects its ability to resist abrasion under the scouring action of high-speed water containing sand and stone. Xie and Lou (2014) studied the abrasive effect of steel balls on a concrete surface driven by high-speed water flow. The results show that the abrasion resistance of concrete initially increases with increasing RP content to a maximum at 15% and then decreases. Kang and Fan (2011) studied the abrasion effect of high-speed sand-containing water flow on a concrete surface and compared the abrasion resistance of concrete mixed with RPs with reference concrete and silica powder concrete. The test results show that the abrasion resistance follows RC > silica powder concrete > NC, and the former increases with increasing RP content.

The improvement of concrete abrasion resistance used in water conservancy projects by the addition of RPs is particularly outstanding. The main performance aspects are that (1) concrete shows improved abrasion resistance with high RP content and (2) the abrasion resistance of RC is better than that of silicon powder concrete with higher strength. This contrasts with the previous

Table 1 Cement properties

Setting time		Compressive strength		Flexural strength	
Initial	Final	3 days	28 days	3 days	28 days
175 min	288 min	22.2 MPa	46.8 MPa	4.6 MPa	8.7 MPa

Fig. 1 RPs: 1–3 mm (left) and 3–5 mm (right)

Table 2 Aggregate properties

Material	Size (mm)	Apparent density (kg/m^3)	Mud content (%)	Crushed index (%)	Fineness modulus
Coarse aggregates	5–20	2732	0.38	8.9	–
Fine aggregates	0–4.75	2668	1.3	–	2.7

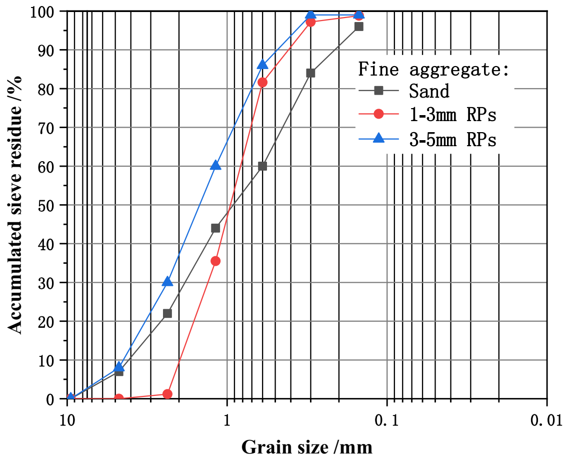


Fig. 2 Grading curves of sand and RPs

understanding that high concrete strength is associated with high abrasion resistance. The addition of RPs can therefore be concluded to have promising application prospects for hydraulic structures that require high concrete abrasion resistance. However, few experimental data are available regarding the abrasion resistance of RC used in water conservancy projects and a systematic understanding of the influence and mechanism is lacking. To address this question, we pretreated RPs of different size intervals (1–3 and 3–5 mm) using three solutions (water washing, NaOH solution, and KH570) and compared the effect of RP content on the abrasion resistance of RC with that of two kinds of prepared reference concrete (NC, C30 and C50). The RC compositions were prepared by replacing part of the fine aggregate with RPs according to the volume fraction. The effect and mechanism of RP size, RP content, and pretreatment protocol on the impact resistance and abrasion resistance of concrete were studied.

2 Experiment

2.1 Materials

Ordinary Portland cement 42.5 was used in this study and its properties are listed in Table 1 and the properties of cement meet the requirements of GB175-2007 (2007). The coarse aggregates were limestone gravel, the fine aggregates were natural river sand, and the RPs of 1–3 mm and 3–5 mm in size (Fig. 1) were obtained from crushed scrap tires. The properties of the coarse and fine aggregates are listed in Table 2. The apparent density of the RPs is 1119 kg/m^3. The grading curve of the fine aggregates and RPs is shown in Fig. 2**.** The indexes of the fine and coarse aggregates meet the requirements of GB/T14684-2011 (2011) and GB/T14685-2011 (2011).

2.2 Mixtures

The mixture ratio of the NC of two strength grades C30 (RP content = 0 in group A) and C50 (RP content = 0 in group B) is listed in Table 3. Based on the mix ratio of NC (or reference concrete), RC is prepared by replacing sand with RPs according to a certain volume fraction (RP content = 10%, 15%, 20% in group A and group B), which is listed in Table 3.

2.3 Test and Specimen Preparation

Slump tests, cube compressive strength tests, splitting tensile strength tests, and abrasion resistance tests were performed on the concrete samples. The concrete mixing, specimen preparation, and test protocol was followed according to the test code for hydraulic concrete SL352-2006 (2006).

Abrasion resistance tests were carried out using the underwater-steel-ball method according to the

Table 3 Concrete mixture proportions (kg/m^3)

Group	Mixtures	Water	Cement	Crushed stones	Sand	RPs	RP content
A	C30-0	190	350	1180	680	0	0%
	C30-10	190	350	1180	612	28	10%
	C30-15	190	350	1180	578	42	15%
	C30-20	190	350	1180	544	56	20%
B	C50-0	158	472	1170	680	0	0%
	C50-10	158	472	1170	612	28	10%
	C50-15	158	472	1170	578	42	15%
	C50-20	158	472	1170	544	56	20%

Fig. 3 Concrete specimen and steel balls

Fig. 4 Ball-abrasion machine

test code for hydraulic concrete (SL352-2006, 2006). The concrete specimens were disks with a diameter of 300 mm and height of 100 mm (Fig. 3). A steel ball grinding instrument was used, as shown in Fig. 4.

The water flow was driven by a 1200 r/min agitator. Seventy steel balls of different diameters (10, 35, and 25 balls with diameters of 25.4, 19.1, and 12.7 mm, respectively; Fig. 3) were driven by the water flow to grind the concrete surface for 72 h. The concrete specimens were soaked in water for 48 h prior to grinding. The surface moisture was removed by wiping prior to weighing before and after grinding. The abrasion resistance of concrete is expressed by R_a(h·m^2·kg^{-1}) calculated according to:

Table 4 Specimen number and size for each group

Test	Number	Size
Cube compressive strength	3	150 mm × 150 mm × 150 mm
Splitting tensile strength	3	150 mm × 150 mm × 150 mm
Abrasion resistance	3	Ø 300 mm × 100 mm

$$R_a = \frac{TA}{M_T}, \tag{1}$$

where T (h) is the accumulated test time, A (m^2) is the area of concrete specimens subjected to abrasion, and M_T (kg) is the accumulated mass loss of the concrete specimens after abrasion.

The concrete specimens can be divided into 14 groups (7 groups in group A and 7 groups in group B) according to the strength grade (C30 and C50) of the reference concrete, the RP size (1–3 mm and 3–5 mm) and the RP content (10%, 15% and 20%) of RPs mixed. The number and size required for performance test of each group of concrete specimens are listed in Table 4.

2.4 RP Pretreatment

The RPs used in this study are made from scrap car tires through mechanical crushing. Numerous additives in car tires, such as carbon black, zinc oxide, and aromatic compounds, exposed on the surface of the RPs weaken the bonding force between the RPs and cement stone, thus harming the strength of RC. Therefore, some modification methods have been developed to remove the additives to reduce the hydrophobicity of RPs and enhance the bonding quality between RPs and cement stone:

(1) Water processing: RPs were poured into clean water and stirred. The RPs were cleaned several times until the water was not turbid, then removed and

dried. Water processing is a physical method to remove the additives from RPs.

(2) NaOH solution processing: 1% mass concentration of NaOH solution was prepared and the RPs were poured into the solution and soaked for 24 h to allow the chemical reaction in the solution to be fully completed. The RPs were then repeatedly cleaned with water until the water pH reached neutral (as measured using pH test paper). The RPs were then removed and dried. NaOH solution processing is a chemical method to remove zinc stearate (the reaction product of zinc oxide and stearic acid) from the surface of RPs (Khern et al., 2020; Liu et al., 2016; Youssf et al., 2016).

(3) NaOH + KH570 processing: after the RPs were treated with the above NaOH solution and dried, KH570 with a mass of 1% of the RPs was weighed and diluted with a certain amount of anhydrous ethanol and poured into the RPs. The RPs were wet during this process. KH570 is a coupling agent with two functional groups of different properties. One part of the functional group can react with organic molecules and the other part can react with the adsorption water on the surface of inorganic substances to form a firm bond. In the NaOH + KH570 processing, KH570 can be better placed between RPs and cement stone after removing the surface additive of RPs by NaOH solution.

The RP pretreatment effect is only related to the pretreatment method, and has nothing to do with the RP content. In order to simplify the test, this paper only treated the RPs with RP content = 15%.

3 Results and Discussion

3.1 Slump of the Concrete Mixtures

The slump of concrete mixture with the RPs content as shown in Fig. 5.

The slump of the RC mixtures initially increases with increasing RP content and then decreases, as shown in Fig. 5. For RP content = 15%, the slump of the RC mixture increases by 13.3% (1–3 mm) and 9.3% (3–5 mm) compared with reference concrete.

RPs are organic materials, compared with inorganic material sand, in water absorption and hardness has a big difference. The water absorption and hardness of RPs are less than that of sand, and the RPs are angular and roundness is worse than that of sand. When the sand are replaced by RPs with a small amount (10% and 15%), the slump of concrete mixture increases due to the release of free water. When the sand are replaced by RPs with a large amount (20%), the RPs with sharp angles are more easily deformed, which increases the internal friction angle of the concrete mix, and makes the slump of the concrete mix show a decreasing trend.

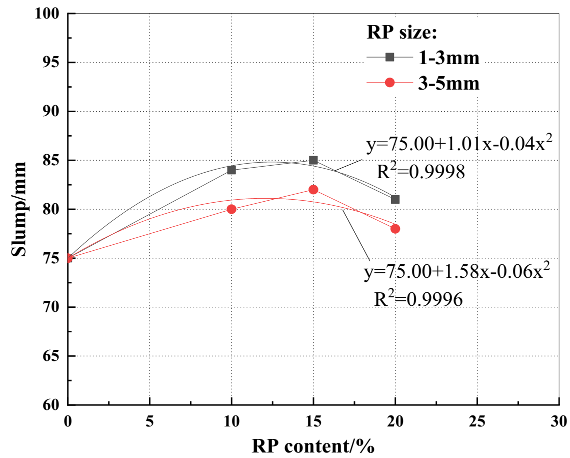


Fig. 5 Relationship between the slump of the group A concrete mixture and RP content

Khatib and Bayomy (1999) showed that the slump of RC decreases with increasing RPs, which differs significantly from the results obtained here likely owing to the different process by which the tire was ground into RPs (Bravo & Brito, 2012; Khatib & Bayomy, 1999).

For the same RP content, the slump was found to be higher for CRA mixed with smaller RPs (1–3 mm) than that for larger RPs (3–5 mm), which is consistent with previous results by Eldin and Senouci (1994) and Taha et al. (2008).

Origin software was used to fit the relationship curve between the slump and RP content, shown in Fig. 5. A y-intercept of 75.00 is required and the obtained equations are:

$$\boldsymbol{y} = 75.00 + 1.01\boldsymbol{x} - 0.04\boldsymbol{x}^2, \tag{2}$$

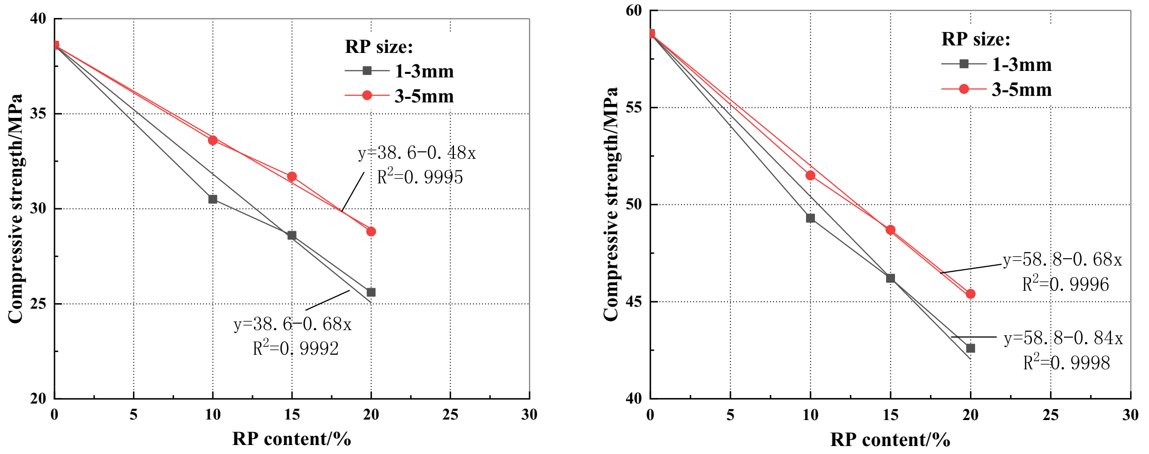
for 1–3 mm RPs and

$$\boldsymbol{y} = 75.00 + 1.58\boldsymbol{x} - 0.06\boldsymbol{x}^2, \tag{3}$$

for 3–5 mm RPs, where $\boldsymbol{x}$ represents RPC (%) and $\boldsymbol{y}$ represents slump (mm). The $\boldsymbol{x}^2$ coefficients in Eqs. (2) and (3) are similar and their average is taken to combine these equations as:

$$\boldsymbol{y} = 75.00 + \boldsymbol{\alpha x} - 0.05\boldsymbol{x}^2, \tag{4}$$

where α is a coefficient related to the RP size and equal to 1.01 and 1.58 when using 1–3 mm and 3–5 mm RP sizes, respectively.



(a) Group A **(b)** Group B

Fig. 6 Relationship between the compressive strength of concrete and RP content

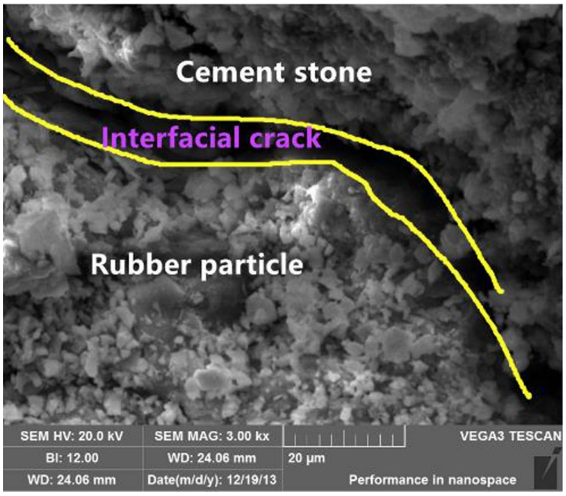


Fig. 7 Bonding of RPs to cement stone

3.2 Compressive Strength

The influence of RPs on the compressive strength of concrete is shown in Fig. 6.

The compressive strength of concrete decreases linearly with increasing RP content, consistent with several previous studies (Gregori et al., 2019; Hadzima-Nyarko et al., 2019; Huang et al., 2020; Williams & Partheeban, 2018). The main reasons are that: (1) RPs themselves are much less strong than sand; (2) RPs are organic matter, while sand and cement stone are inorganic, so the bond quality of RPs and cement stone is not as good as that of sand and cement stone, and innate micro-cracks have appeared between RPs and cement stone bonding surface (as shown in Fig. 7).

For the same RP content, the reduction of compressive strength is greater for RC with small RPs (1–3 mm) than CRA with large RPs (3–5 mm), which is in agreement with the results of Skripkiunas et al. (2009) but differs from those of Raffoul et al. (2016) and Gesoglu et al. (2015). For the same RPC, the number of smaller RPs is higher than larger RPs, the air suction effect is larger, and more defects are introduced.

The fitted curves in Fig. 6 yield y-intercepts of 38.6 and 58.8 for groups A and B, respectively, and the linear relationship is given as:

$$y = 38.6 - 0.68x(\text{Group A}), \tag{5}$$

$$y = 58.8 - 0.84x(\text{Group B}), \tag{6}$$

for 1–3 mm RPs and

$$y = 38.6 - 0.48x(\text{Group A}), \tag{7}$$

$$y = 58.8 - 0.68x(\text{Group B}), \tag{8}$$

for 3–5 mm RPs, where y represents compressive strength (MPa). Combining Eqs. (5) and (7) yields:

$$y = 38.6 - \alpha x(\text{Group A}), \tag{9}$$

where $\alpha = 0.68$ for 1–3 mm RPs and $\alpha = 0.48$ for 3–5 mm RPs. Combining Eqs. (6) and (8) yields:

$$y = 58.8 - \alpha x\ (\text{Group B}), \tag{10}$$

where $\alpha = 0.84$ for 1–3 mm RPs and $\alpha = 0.68$ for 3–5 mm RPs.

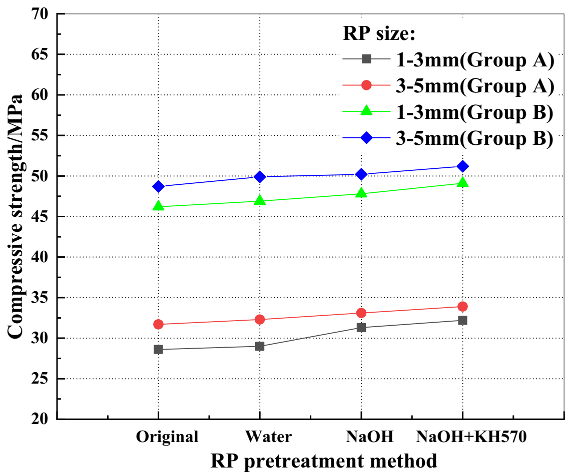


Fig. 8 Effect of different rubber pretreatment methods on the compressive strength

The RPs were pretreated as described in Sect. 2.4 and the change of compressive strength of the RC before and after treatment is compared for RPC = 15%, as shown in Fig. 8.

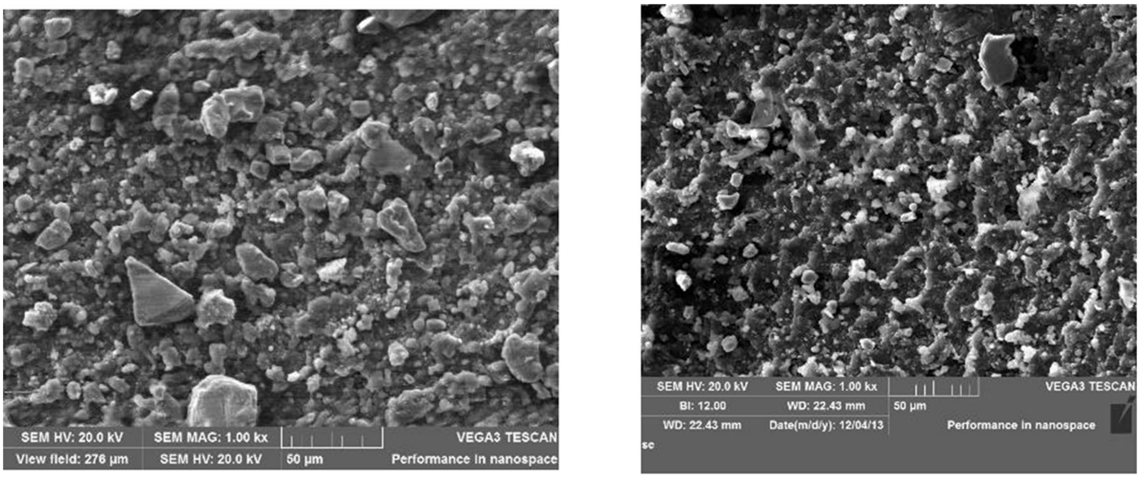
The treated RPs are found to improve the compressive strength of CRA to some extent. In particular, these treatments can remove dust, zinc stearate, and other substances from the RP surface (Khern et al., 2020; Liu et al., 2016; Segre et al., 2002; Youssf et al., 2016), which makes the RP surface more rough and conducive to the bonding of RPs and cement stone, as shown in scanning electron microscope images in Fig. 9. The bonding interface between treated RPs and cement stone is greatly improved compared with that before treatment, as shown in Fig. 10. Compared with Fig. 7, the RP in Fig. 10 bond more closely with the cement stone, and the interfacial crack of the bonding interface is almost invisible, indicating that the RPs have improved the bonding quality with the cement stone after treatment.

The NaOH + KH570 treatment method shows the best effect with an increased compressive strength of the RC by 12.5% (1–3 mm (group A)), 7.1% (3–5 mm (group A)), 6.3% (1–3 mm (group B)), and 5.1% (3–5 mm (group B)) compared with the pretreatment values. KH570 has both organic chemical bond and inorganic chemical bond to build a bridge between RPs and cement stone, so that RPs and cement stone are well bonded. The effect of the NaOH + KH570 treatment becomes less apparent with increasing strength grade of the reference concrete.

3.3 Splitting Tensile Strength

The influence of RPs on the splitting tensile strength of concrete is shown in Fig. 11.

A comparison of Figs. 6 and 11 shows that the influence of RP content on the splitting tensile strength of concrete is consistent with that of compressive strength. The reason for the decrease of concrete splitting tensile strength is the same as the reason for the decrease of compressive strength, that is, the replacement of sand by RPs brings a lot of weak interface to the concrete inside. But the difference is that the reduction range of the splitting tensile strength with increasing RP content is significantly smaller than that of compressive strength.



(a) Before solution treatment (b) After solution treatment

Fig. 9 Effect of RP pretreatment methods on the compressive strength

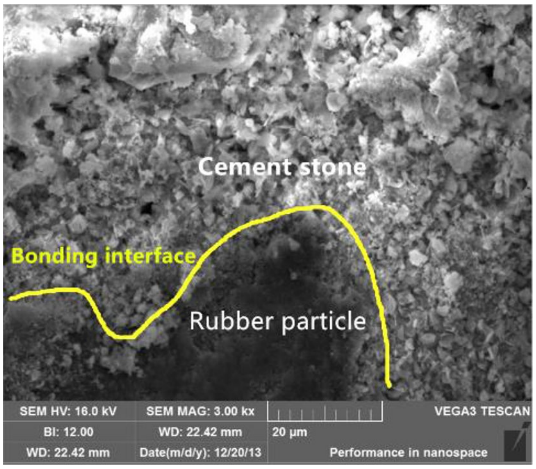


Fig. 10 Electron microscope image of adhesive interface between treated RP and cement stone

The fitted curves in Fig. 11 have *y*-intercepts of 3.03 and 3.78 for groups A and B, respectively, and the linear relationship is obtained as follows:

$$y = 3.03 - 0.04x(\text{Group A}), \tag{11}$$

$$y = 3.78 - 0.05x(\text{Group B}), \tag{12}$$

for 1–3 mm RPs and

$$y = 3.03 - 0.02x(\text{Group A}), \tag{13}$$

$$y = 3.78 - 0.04x(\text{Group B}), \tag{14}$$

for 3–5 mm RPs, where $\boldsymbol{y}$ in these equations represents the splitting tensile strength (MPa)**.** Combining Eqs. (11) and (13) yields:

$$y = 3.03 - \boldsymbol{\alpha x}(\text{Group A}), \tag{15}$$

where α = 0.04 for 1–3 mm RPs and α = 0.02 for 3–5 mm RPs. Combining Eqs. (12) and (14) yields:

$$y = 3.78 - \boldsymbol{\alpha x}(\text{Group B}), \tag{16}$$

where α = 0.05 for 1–3 mm RPs and α = 0.04 for 3–5 mm RPs.

Fig. 12 shows that the addition of treated RPs improves the splitting tensile strength of RC.

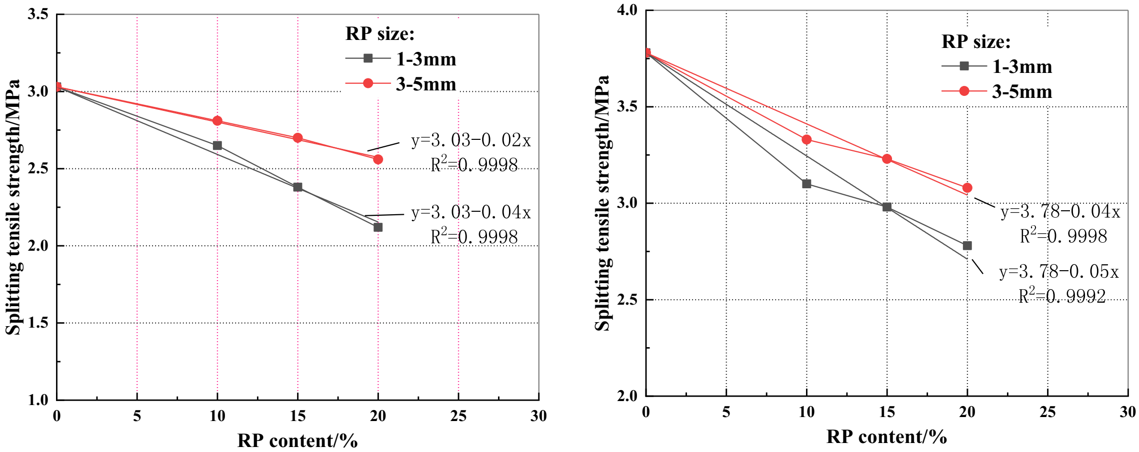
The NaOH + KH570 treatment method has the best effect and increases the RC splitting tensile strength by 17.2% (1–3 mm (group A)), 8.9% (3–5 mm (group A)), 13.0% (1–3 mm (group B)), and 11.8% (3–5 mm (group B)) compared with the pretreatment values.

3.4 Abrasion Resistance

3.4.1 Effect of RPs on RC Abrasion Resistance

The effect of RPs on RC abrasion resistance is shown in Fig. 13.

The abrasion resistance of concrete increases with increasing RP content, which is consistent with previous studies (Kang & Fan, 2011; Xie & Lou, 2014). Xie and Lou (2014) proposed a maximum abrasion resistance of concrete with RP content = 15% and that the abrasion resistance of concrete with RP content = 30% is lower than that of concrete without RPs, which differs from the results obtained here. Although 30% RP content was not investigated here, an extrapolation of the growth trend of our



(a) Group A **(b)** Group B

Fig. 11 Relationship between the compressive strength of concrete and RP content

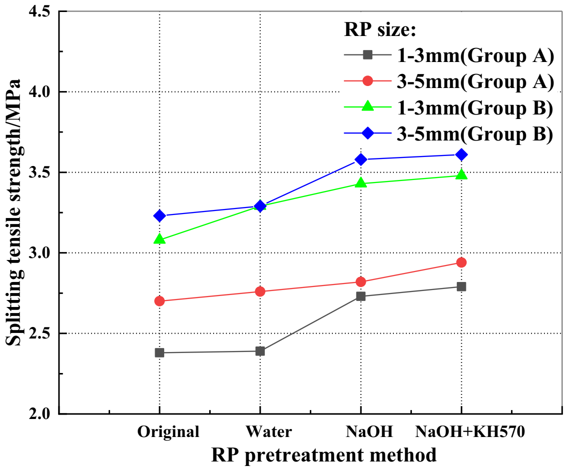


Fig. 12 Effect of different RP pretreatment methods on the compressive strength

results in Fig. 13 indicates that the abrasion resistance of concrete with RP content = 30% will not be lower than that of concrete.

The RPs have better energy absorption because their deformation ability and toughness are much greater than aggregate, which is equivalent to forming an elastic protective layer on the surface of concrete, which extends the grinding damage time to a large extent, thus making the concrete show a higher grinding resistance strength.

Fig. 13 shows that the surface of RC is smoother than that of reference concrete, and higher RP content is associated with smoother RC surfaces. This is very important because rough concrete surfaces are easier to erode under high-speed water flow and the abrasive effect of sand within the water flow. Cavitation erosion will also accelerate the abrasion of the concrete surface. In contrast, a relatively flat surface greatly reduces the probability of cavitation. Even if cavitation erosion occurs on the surface of RC, its destructive force will be mostly absorbed by the RPs and the cement stone will not be destroyed. High-RP-content RC is therefore suggested to be a promising material for hydraulic structure engineering.

The fitted curves in Fig. 13 require fixed y-intercepts of 4.73 and 7.37 for groups A and B, respectively, and the obtained linear formulas are:

$$\boldsymbol{y} = 4.73 - 0.12\boldsymbol{x} + 0.02\boldsymbol{x}^2 \text{(Group A)}, \tag{17}$$

$$\boldsymbol{y} = 7.37 + 0.09\boldsymbol{x} + 0.01\boldsymbol{x}^2 \text{(Group B)}, \tag{18}$$

for 1–3 mm RPs and

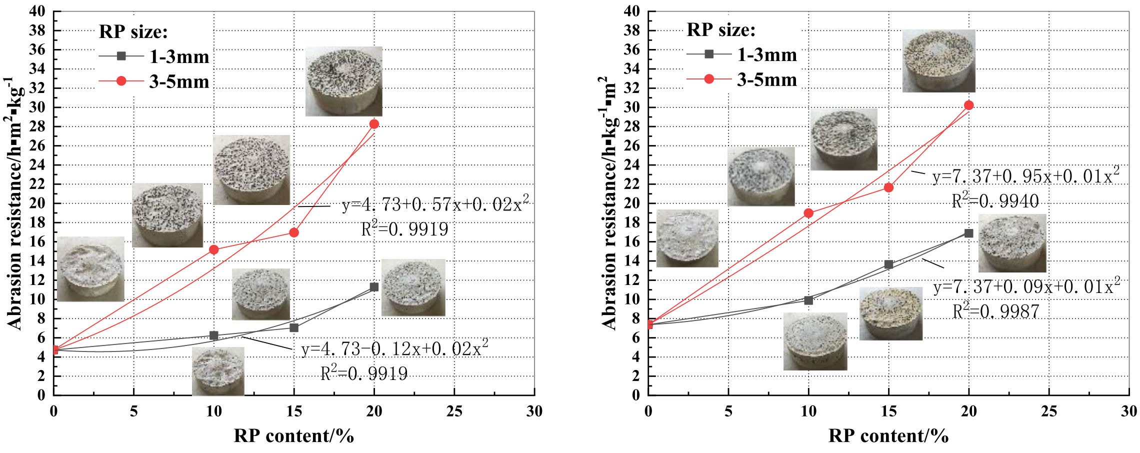
$$\boldsymbol{y} = 4.73 + 0.57\boldsymbol{x} + 0.02\boldsymbol{x}^2 \text{(Group A)}, \tag{19}$$

$$\boldsymbol{y} = 7.37 + 0.95\boldsymbol{x} + 0.01\boldsymbol{x}^2 \text{(Group B)}, \tag{20}$$

for 3–5 mm RPs, where $\boldsymbol{y}$ in these equations represents the abrasion resistance ($\text{h}\cdot\text{m}^2\cdot\text{kg}^{-1}$). Combining Eqs. (17) and (19) for group A yields:

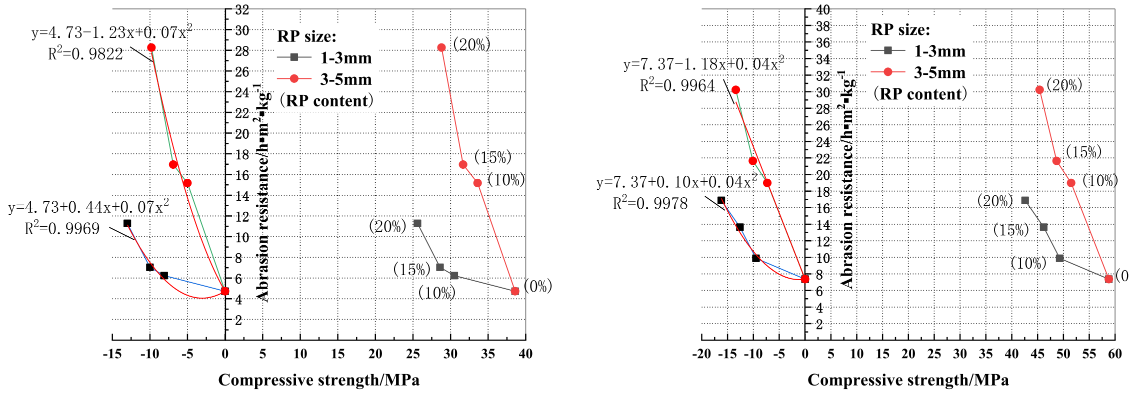
$$\boldsymbol{y} = 4.73 + \boldsymbol{\alpha x} + 0.02\boldsymbol{x}^2 \text{(Group A)}, \tag{21}$$

where $\alpha = -0.12$ for 1–3 mm RPs and $\alpha = 0.57$ for 3–5 mm RPs. Combining Eqs. (18) and (20) for group B yields:



(a) Group A (b) Group B

Fig. 13 Abrasion resistance as a function of RP content



(a) Group A (b) Group B

Fig. 14 Relationship between the compressive strength and abrasion resistance of concrete

$$y = 7.37 + \alpha x + 0.01x^2 (\text{Group B}), \tag{22}$$

where α = −0.09 for 1–3 mm RPs and α = 0.95 for 3–5 mm RPs.

3.4.2 Effect of Concrete Compression Strength on RC Abrasion Resistance

RPs exert a range of effects on the properties of concrete. While RPs greatly improve the abrasion resistance of concrete, they also strongly reduce its compressive strength, as shown in Fig. 14.

Higher concrete strength is generally thought to be associated with higher abrasion resistance strength (Mehta & Gjqrv, 1982; Toutanji et al., 1998). The U.S. Bureau of Reclamation (Han, 1996) test shows that the relationship between the abrasion resistance strength and compressive strength of concrete is:

$$R_A = 0.00219R + 0.329, \tag{23}$$

where R_A (h/cm) is the abrasion resistance and R (MPa) is the compressive strength. Equation (23) shows that the abrasion resistance of concrete is proportional to its compressive strength. However, the abrasion resistance of RC differs from that of silicon powder concrete and steel fiber concrete, which contrasts with the direct proportional relationship shown in Eq. (23).

The relationship between abrasion resistance and compression strength shown in Fig. 14 is slightly deformed and shifted in the negative x-direction. The fitted curves in Fig. 14 require fixed y-intercepts of 4.73 and 7.37 for groups A and B, respectively, and the polynomials are given as:

$$y = 4.73 + 0.44(x - 38.6) + 0.07(x - 38.6)^2 (\text{Group A}), \tag{24}$$

$$y = 7.37 + 0.10(x - 58.8) + 0.04(x - 58.8)^2 (\text{Group B}), \tag{25}$$

for 1–3 mm RPs and

$$y = 4.73 - 1.23(x - 38.6) + 0.07(x - 38.6)^2 (\text{Group A}), \tag{26}$$

$$y = 7.37 - 1.18(x - 58.8) + 0.04(x - 58.8)^2 (\text{Group B}), \tag{27}$$

for 3–5 mm RPs, where x represents the compressive strength (MPa) and y represents the abrasion resistance ($\text{h}\cdot\text{m}^2\cdot\text{kg}^{-1}$). Combining Eqs. (24) and (26) yields:

$$y = 4.73 + \alpha(x - 38.6) + 0.07(x - 38.6)^2 (\text{Group A}), \tag{28}$$

where α = 0.44 for 1–3 mm RPs and α = −1.23 for 3–5 mm RPs. Combining Eqs. (25) and (27) yields:

$$y = 7.37 + \alpha(x - 58.8) + 0.04(x - 58.8)^2 (\text{Group B}), \tag{29}$$

where α = 0.10 for 1–3 mm RPs and α = −1.18 for 3–5 mm RPs.

3.4.3 Effect of Reference Concrete Strength on RC Abrasion Resistance

The effect of reference concrete strength on RC abrasion resistance is shown in Fig. 15.

As mentioned in the previous section, the negative proportionality between the abrasion resistance and compressive strength of RC is only valid for the same reference concrete (i.e., when RP content is the only factor that changes). For the same RP size and content, the RC prepared with reference concrete with high compressive

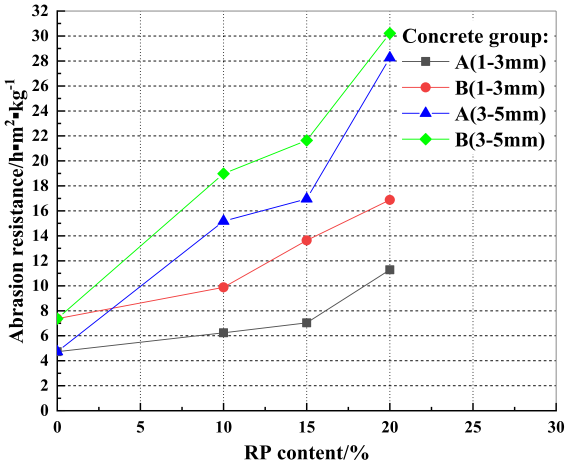


Fig. 15 Relationship between the abrasive resistance of concrete and RP content

strength has high abrasion resistance (Fig. 15), which is thus generally preferred in hydraulic engineering. However, for RC, the main factor that determines its abrasion resistance is the RP content rather than the compressive strength. Fig. 15 clearly shows that the abrasion resistance of group A with 20% RP content is higher than that of the reference concrete in group B. Similarly, the abrasion resistance of RC in group A is higher than that of the reference concrete in group B, and the abrasion resistance of RC in group A with 20% RP content is higher than that of RC with 10% and 15% RP content in group B. Therefore, there are two choices for hydraulic engineering designers when using RC as a structural material with high abrasion resistance: (1) RC with high compressive strength, high abrasion resistance, and low RP content; or (2) RC with high abrasion resistance, low compressive strength that still meets the design requirements, and high RP content. To obtain a high-RP-content RC with high abrasion resistance, it is necessary to reduce the water-cement ratio and improve the strength of the corresponding reference concrete. When the RP content is large, it is not necessary to reduce the water–cement ratio to obtain RC with high abrasion resistance, but attention must be paid regarding whether or not the compressive strength meets the engineering requirements. In hydraulic engineering, the bearing capacity of the concrete structure responsible for abrasion resistance is not particularly high.

3.4.4 Effect of RP Treatment Method on RC Abrasion Performance

This section discusses the influence of RP treatment protocol (see Sect. 2.4) on the abrasion resistance of RC, as shown in Fig. 16.

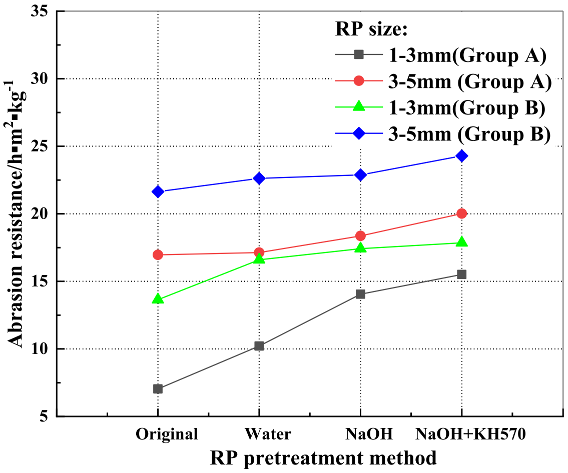


Fig. 16 Effect of different RP pretreatment methods on the abrasion resistance

The results show that the treated RPs can improve the abrasion resistance of RC to a certain extent. This is mainly because the treated RPs increase the compressive strength of RC compared with the pretreatment value (see Sect. 3.2). The NaOH + KH570 treatment method used here has the best effect and the abrasion resistance of the RC after treatment is higher than the pretreatment value by factors of 120% (1–3 mm (group A)), 18% (3–5 mm (group A)), 30% (1–3 mm (group B)), and 10% (3–5 mm (group B)). The effect of NaOH + KH570 treatment decreases with increasing strength grade of the reference concrete.

3.4.5 Comparison of RC Abrasion Resistance Improvement Methods

The above analysis indicates three ways to improve the abrasion resistance of CRA: (1) increase the RP content (within 20%); (2) improve the strength of the reference concrete (i.e., reduce the water-cement ratio); and (3) modify the RPs. The following is a comparative analysis of the three methods using the abrasion resistance of RC with RP content = 15% and 3–5 mm RP size as an example.

The abrasion resistance of RC with C30 as the reference concrete and 3–5 mm rubber size mixed with

Table 5 Abrasion resistance of typical RC

Strength grade of reference concrete	Abrasion resistance of RC(h m^2 kg^{-1})		
	15%	20%	NaOH + KH570
C30	16.96	28.26	20.02
C50	21.64	–	–

15% RP content is 16.96 h • m^2 • kg^{-1} (Table 5). When the RP content is increased to 20%, the abrasion resistance increases by 66.6%. When the reference concrete is increased to C50, the abrasion resistance increases by 27.6%. When the RPs is pretreated with NaOH + KH570, the abrasion resistance increases by 18.0%. Increasing the RP content can significantly improve the abrasion resistance of RC (from 15 to 20%), followed by increasing the strength grade of the benchmark concrete (from C30 to C50), and finally, the pretreatment of RPs by NaOH + KH570. These results provide guidance for hydraulic engineering design.

4 Mechanism of Concrete Abrasion Resistance

There are two main external conditions of hydraulic concrete abrasion: (1) water flow with a certain amount of solid particles and (2) higher flow velocity that starts the flow of solid particles and reaches a certain speed. Flow velocity is the key factor that affects the abrasive wear of concrete. When the flow velocity exceeds the starting velocity of solid particles and remains low, the solid particles roll or slide over the concrete surface, which causes a friction-loss or micro-cutting effect on concrete. When the water velocity exceeds the starting speed and the flow velocity is very high, the solid particles are likely to rapidly roll or jump forward, thus the solid particles have a greater damage impact on the concrete. The wear of hydraulic concrete can therefore be considered as the hydrodynamic abrasive wear of solid particles acting on the concrete surface at different impact angles, where sand particle micro-cutting and impact deformation simultaneously erode the concrete. The total amount of wear is the superposition of the two wear types. The composite abrasive wear formula proposed by Nelson and Gilchrist is given as (Han, 1996):

$$\boldsymbol{I(\alpha)} = \frac{\boldsymbol{W(\alpha)}}{\boldsymbol{M_s}} = \frac{1}{2\boldsymbol{\varepsilon}}(\boldsymbol{V_s sin\alpha} - \boldsymbol{K})^2 + \frac{1}{2\boldsymbol{\varphi}}\boldsymbol{V_s^2 cos^2\alpha \bullet sin(n\alpha)} \quad (\boldsymbol{\alpha} \le \boldsymbol{\alpha_0}), \tag{30}$$

$$\boldsymbol{I(\alpha)} = \frac{\boldsymbol{W(\alpha)}}{\boldsymbol{M_s}} = \frac{1}{2\boldsymbol{\varepsilon}}(\boldsymbol{V_s sin\alpha} - \boldsymbol{K})^2 + \frac{1}{2\boldsymbol{\varphi}}\boldsymbol{V_s^2 cos^2\alpha} \quad (\boldsymbol{\alpha} > \boldsymbol{\alpha_0}), \tag{31}$$

where $\boldsymbol{I(\alpha)}$ (g/kg) is the wear weight loss rate, $\boldsymbol{M_s}$ (kg) is the mass of abrasive sand, $\boldsymbol{W(\alpha)}$ (g) is the weight loss of material worn away by sand with $\boldsymbol{M_s}$ weight at angle α, $\boldsymbol{V_s}$ is the sand velocity (m/s), $\boldsymbol{\alpha}$ (°) is the impact angle, $\boldsymbol{\alpha_0}$ (°) is the critical impact angle, where $\boldsymbol{\alpha_0} = \frac{\pi}{2n}$, $\boldsymbol{K}$ (m/s) is the critical sand velocity (when $\boldsymbol{V_s sin\alpha} \le \boldsymbol{K}$,$\boldsymbol{I(\alpha)} = 0$, $\boldsymbol{\varepsilon}$ (kg·m^2/(g·s^2)) is the impact wear energy dissipation factor, $\boldsymbol{\varphi}$ (kg·m^2/(g·s^2)) is the micro-cutting wear energy dissipation factor, and $\boldsymbol{n}$ is the horizontal rebound factor. Equations (30) and (31) can describe the material grinding condition when the grinding characteristic parameters of $\boldsymbol{K}$, $\boldsymbol{\varepsilon}$, $\boldsymbol{\varphi}$, and $\boldsymbol{n}$ are determined. The material properties have a significant influence on the relationship between wear and impact angle (Han, 1996). The loss of flexible material is mainly caused by the plastic deformation process and cutting action of the material. The cutting action of the abrasive particles erodes the material surface. The loss of brittle material is mainly due to the repeated impact of abrasive particles on the material surface and the formation of radial surface cracks. The cracks eventually tend to interlace, which results in material spalling.

In this paper, the abrasion of steel balls on the concrete is the primary form of impact, while sliding or rolling damage to the concrete surface is very limited. Suppose a steel ball of mass m hits the concrete surface with a velocity V and impact angle $\boldsymbol{\alpha}$, and bounces back with the same velocity V. A cutting force will be produced in the horizontal direction on the concrete surface and vertical direction of the concrete surface impact. The impact force F_y should be analyzed according to the principle of kinetic energy (ignoring the resistance of water):

$$\boldsymbol{F_y} = \frac{2\boldsymbol{mVcos\alpha}}{\Delta\boldsymbol{t}}, \tag{32}$$

where $\Delta\boldsymbol{t}$ is the impact time of the steel ball on the concrete surface. Because $\Delta\boldsymbol{t}$ is small, the value of $\boldsymbol{F_y}$ is large. The ball bounces under the reaction force and then falls back down and hits the concrete again. Under repeated cutting and impact, the concrete strength reaches a fatigue limit value and damage such as surface spalling occurs. The strength of the reference cement stone is lower than that of the aggregate and thus reaches its fatigue limit first and is worn away, leaving pits in its original positions from which the aggregate gradually protrudes. A coarse and bulging aggregate will thus bear more ball impacts than a concave cement stone. Under the action of ball cutting and impact, the entire lump of coarse aggregate will ultimately fall off or be gradually rubbed flat, and a tangential line from the ball impact on by the cement stone will gradually increase. This reciprocating cycle abrades the concrete surface. The RPs in RC act like an elastic layer, as shown in Fig. 13, which increases $\Delta\boldsymbol{t}$ and reduces the $\boldsymbol{F_y}$ value and bounce rate, thus largely prolonging the concrete unit mass abrasion resistance time. Even if the first layer of RPs is rubbed away after grinding, additional RPs within the cement stone will be exposed to form a new layer of elastic protection.

5 Conclusions

In this paper, several tests were performed on various concrete compositions, including slump, compressive strength, splitting tensile strength, abrasion resistance, and grinding performance, and the effect of RP size and dosage is discussed. The conclusions can be summarized as follows:

- The slump of RC initially increases with increasing RP content and then decreases. The slump of RC with smaller RPs is larger than that with larger RPs.
- The compressive strength and splitting tensile strength of RC decrease linearly with increasing RP content, and the former is greater for RC with larger rubber particles. The reduction range of the splitting tensile strength with increasing RP content is less than that of the compressive strength. The rubber pretreatment method can improve the compressive strength and splitting tensile strength of RC, for which the NaOH + KH570 treatment has the best effect.
- The abrasion resistance of RC increases with increasing RP content. For the same RP content, RC with large RPs has a higher abrasion resistance than the RC with small RPs.
- For RC with the same RP size, RP content, and reference concrete, the abrasion resistance is inversely proportional to the compressive strength.
- The RP content has the greatest influence on RC abrasion resistance, followed by compressive strength. RP pretreatment methods can improve the abrasion resistance of RC, of which the NaOH + KH570 treatment yields the best response.

Acknowledgements
The authors would like to acknowledge participation of Master team of College of Geosciences and Engineering in the experimental works, and particularly appreciate the valuable comments made by the editors and reviewers to make a substantial improvement to this manuscript.

Authors' contributions
LF: writing the manuscript, experimental works, analyzing data, reviewing, editing. AC and HL: review and comments. All authors read and approved the final manuscript.

Funding
This study was supported by the National Key R & D Program of China (NO. 2019YFC1509704), the National Natural Science Foundation of China (NO. U1704243), and the Doctoral Candidate Innovation Fund of the North China University of Water Resources and Electric Power (NO. B2019081813).

Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Author information
Ling-Yun Feng: Ph.D. Student, College of Geosciences and Engineering, Geotechnical Engineering Research Institute, Henan Provincial Key Laboratory of Geomechanics and Structural Engineering.Ai-Jiu Chen: Ph.D. Professor, Doctoral advisor, School of Water Conservancy.Han-Dong Liu: Ph.D. Professor, Doctoral advisor, Academic leader.

Received: 2 April 2021 Accepted: 21 August 2021

References

Aliabdo, A. A., Elmoaty, A. E. M. A., & AbdElbaset, M. M. (2015). Utilization of waste rubber in non-structural applications. *Construction and Building Materials, 91*, 195–207. https://doi.org/10.1016/j.conbuildmat.2015.05.080

Al-Tayeb, M. M., Abu Bakar, B. H., Akil, H. M., & Ismail, H. (2012). Effect of partial replacements of sand and cement by waste rubber on the fracture characteristics of concrete. *Polymer-Plastics Technology and Engineering, 51*, 583–589. https://doi.org/10.1080/03602559.2012.659307

Aslani, F. (2016). Mechanical properties of waste tire rubber concrete. *Journal of Materials in Civil Engineering*. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001429

Atahan, A. O., & Yücel, A. Ö. (2012). Crumb rubber in concrete: Static and dynamic evaluation. *Construction and Building Materials, 36*, 617–622. https://doi.org/10.1016/j.conbuildmat.2012.04.068

Basheer, M. (2021). Cooperative operation of the Grand Ethiopian Renaissance Dam reduces Nile riverine floods. *River Research and Applications, 6*, 1–10. https://doi.org/10.1002/rra.3799

Bisht, K., & Ramana, P. V. (2017). Evaluation of mechanical and durability properties of crumb rubber concrete. *Construction and Building Materials, 155*, 811–817. https://doi.org/10.1016/j.conbuildmat.2017.08.131

Bravo, M., & Brito, J. D. (2012). Concrete made with used tyre aggregate: Durability related performance. *J. Cleaner Prod., 25*, 42–50.

Eldin, N. N., & Senouci, A. B. (1993). Observations on rubberized concrete behavior. *Cement, Concrete and Aggregates, 15*, 74–84.

Eldin, N. N., & Senouci, A. B. (1994). Measurement and prediction of the strength of rubberized concrete. *Cement and Concrete Composites, 16*, 287–298.

Elom, N. (2012) Human health risk assessment of potentially toxic elements (PTEs) from environmental matrices doctoral dissertation. *Northumbria University*.

GB175-2007. (2007). Common portland cement. *China*.

GB/T14684-2011. (2011). Sand for construction. *China*.

GB/T14685-2011. (2011). Pebble and crushed stone for construction. *China*.

Gesoglu, M., Güneyisi, E., Hansu, O., Ipek, S., & Asaad, D. S. (2015). Influence of waste rubber utilization on the fracture and steel–concrete bond strength properties of concrete. *Construction and Building Materials, 101*, 1113–1121. https://doi.org/10.1016/j.conbuildmat.2015.10.030

Gregori, A., Castoro, C., Marano, G. C., & Greco, R. (2019). Strength reduction factor of concrete with recycled rubber aggregates from tires. *Journal of Materials in Civil Engineering*. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002783

Gupta, T., Chaudhary, S., & Sharma, R. K. (2014). Assessment of mechanical and durability properties of concrete containing waste rubber tire as fine aggregate. *Construction and Building Materials, 73*, 562–574. https://doi.org/10.1016/j.conbuildmat.2014.09.102

Gupta, T., Chaudhary, S., & Sharma, R. K. (2016). Mechanical and durability properties of waste rubber fiber concrete with and without silica fume. *Journal of Cleaner Production, 112*, 702–711. https://doi.org/10.1016/j.jclepro.2015.07.081

Hadzima-Nyarko, M., Nyarko, E. K., Ademovic, N., Milicevic, I., & Sipos, T. K. (2019). Modelling the influence of waste rubber on compressive strength of concrete by artificial neural networks. *Materials, 12*, 1–18. https://doi.org/10.3390/ma12040561

Han, S. (1996). *Concrete engineering damage and repair and reinforcement*. Ocean Press.

Ho, A. C., Turatsinze, A., Hameed, R., & Vu, D. C. (2011). Effects of rubber aggregates from grinded used tyres on the concrete resistance to cracking. *Journal of Cleaner Production, 23*, 209–215. https://doi.org/10.1016/j.jclepro.2011.09.016

Huang, W., Huang, X., Xing, Q., & Zhou, Z. (2020). Strength reduction factor of crumb rubber as fine aggregate replacement in concrete. *Journal of Building Engineering*. https://doi.org/10.1016/j.jobe.2020.101346

Kang, J., & Fan, K. (2011). Abrasion resistance of rubberized concrete. *Journal of Tianjin University, 44*, 727–731.

Khatib, Z. K., & Bayomy, F. M. (1999). Rubberized Portland cement concrete. *Journal of Materials in Civil Engineering, 11*, 206–213.

Khern, Y. C., Paul, S. C., Kong, S. Y., Babafemi, A. J., Anggraini, V., Miah, M. J., & Savija, B. (2020). Impact of chemically treated waste rubber tire aggregates on mechanical, durability and thermal properties of concrete. *Frontiers in Materials, 7*, 1–11. https://doi.org/10.3389/fmats.2020.00090

Li, D., Yan, Z., Gravina, R., & Mills, J. E. (2018). Compressive stress strain behavior of crumb rubber concrete (CRC) and application in reinforced CRC slab. *Construction and Building Materials, 166*, 745–759. https://doi.org/10.1016/j.conbuildmat.2018.01.142

Liu, F., Zheng, W., Li, L., Feng, W., & Ning, G. (2013). Mechanical and fatigue performance of rubber concrete. *Construction and Building Materials, 47*, 711–719. https://doi.org/10.1016/j.conbuildmat.2013.05.055

Liu, H., Wang, X., Jiao, Y., & Sha, T. (2016). Experimental investigation of the mechanical and durability properties of crumb rubber concrete. *Materials, 9*, 1–12. https://doi.org/10.3390/ma9030172

Mehta, P. K., & Gjqrv, O. E. (1982). Properties of Portland cement concrete containing fly ash and condensed silica fume. *Cement and Concrete Research, 12*, 45–47.

Mendis, A. S. M., Al-Deen, S., & Ashraf, M. (2017). Behaviour of similar strength crumbed rubber concrete (CRC) mixes with different mix proportions. *Construction and Building Materials, 137*, 354–366. https://doi.org/10.1016/j.conbuildmat.2017.01.125

Paine, K. A., Dhir, R. K., & Moroney, R. (2002). Use of crumb rubber to aehieve freeze-thaw resisting conerete. *Proceedings of the International Conference on Concrete for Extreme Conditions Scotland, UK: University of Dundee*, pp. 486–498.

Pavlinek, P., Domanski, B., & Guzik, R. (2009). Industrial upgrading through foreign direct investment in Central European automotive manufacturing. *European Urban and Regional Studies, 16*, 43–63.

Raffoul, S., Garcia, R., Pilakoutas, K., Guadagnini, M., & Medina, N. F. (2016). Optimisation of rubberised concrete with high rubber content: An experimental investigation. *Construction and Building Materials, 124*, 391–404. https://doi.org/10.1016/j.conbuildmat.2016.07.054

Savas, B. Z., Ahmad, S., & Fedroff, D. (1997). Freeze-thaw durability of concrete with ground waste tire rubber. *Transportation Research Record, 1574*, 80–88.

Segre, N., & Joekes, I. (2000). Use of tire rubber particles as addition to cement paste. *Cement and Concrete Research, 30*, 1421–1425.

Segre, N., Monteiro, P. J. M., & Sposito, G. (2002). Surface characterization of recycled tire rubber to be used in cement paste matrix. *Journal of Colloid and Interface Science, 248*, 521–523.

Skripkiunas, G., Grinys, A., & Miškinis, K. (2009). Damping properties of concrete with rubber waste additives. *Materials Science, 15*, 266–272.

SL352-2006. (2006) Test code for hydraulic concrete. *China*.

Sukontasukkul, P., & Chaikaew, C. (2006). Properties of concrete pedestrian block mixed with crumb rubber. *Construction and Building Materials, 20*, 450–457.

Taha, M. M. R., El-Dieb, A., El-Wahab, M. A., & Abdel-Hameed, M. (2008). Mechanical, fracture, and microstructural investigations of rubber concrete. *Journal of Materials in Civil Engineering, 20*, 640–649.

Tan, J., Ren, X., Li, Q., Xu, Y., & Xu, K. (2021). Reservoir dam safety in new era. *Yangtze River, 52*, 149–153.

Thomas, B. S., Gupta, R. C., Kalla, P., & Cseteneyi, L. (2014). Strength, abrasion and permeation characteristics of cement concrete containing discarded rubber fine aggregates. *Construction and Building Materials, 59*, 204–212. https://doi.org/10.1016/j.conbuildmat.2014.01.074

Thomas, B. S., Gupta, R. C., & Panicker, V. J. (2016a). Recycling of waste tire rubber as aggregate in concrete: Durability-related performance. *Journal of Cleaner Production, 112*, 504–513. https://doi.org/10.1016/j.jclepro.2015.08.046

Thomas, B. S., Kumar, S., Mehra, P., Gupta, R. C., Joseph, M., & Csetenyi, L. J. (2016b). Abrasion resistance of sustainable green concrete containing waste tire rubber particles. *Construction and Building Materials, 124*, 906–909. https://doi.org/10.1016/j.conbuildmat.2016.07.110

Toutanji, H., Mcneil, S., & Bayasi, Z. (1998). Chloride permeability and impact resistance of polypropylene-fiber-silica fume concrete. *Cement and Concrete Research, 28*, 961–968.

Williams, K. C., & Partheeban, P. (2018). An experimental and numerical approach in strength prediction of reclaimed rubber concrete. *Advances in Concrete Construction, 6*, 87–102. https://doi.org/10.12989/acc.2018.6.1.087

Xie, L., & Lou, Z. (2014). Research on property of abrasion resistance of rubber-filled concrete. *Journal of Water Resources & Water Engineering, 25*, 188–191.

Yang, W., Yang, H., Yang, D., & Hou, A. (2021). Causal effects of dams and land cover changes on flood changes in mainland China. *Hydrology and Earth System Sciences, 25*, 2705–2720. https://doi.org/10.5194/hess-25-2705-2021

Youssf, O., Mills, J. E., & Hassanli, R. (2016). Assessment of the mechanical performance of crumb rubber concrete. *Construction and Building Materials, 125*, 175–183. https://doi.org/10.1016/j.conbuildmat.2016.08.040

Zhang, B., & Li, G. (2012). The abrasion-resistance investigation of rubberized concrete. *Journal of Wuhan University of Technology-Mater. Sci. Ed., 27*, 1144–1148. https://doi.org/10.1007/s11595-012-0619-8

Zhang, Y. M., & Zhao, Z. (2015). Internal stress development and fatigue performance of normal and crumb rubber concrete. *Journal of Materials in Civil Engineering, 27*, 1–10. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001000

Zhu, H., Liang, J., Xu, J., Bo, M., Li, J., & Tang, B. (2018). Research on anti-chloride ion penetration property of crumb rubber concrete at different ambient temperatures. *Construction and Building Materials, 189*, 42–53. https://doi.org/10.1016/j.conbuildmat.2018.08.193

Zhu, R., Pang, J., Wang, T., & Huang, X. (2020). Experimental research on chloride erosion resistance of rubber concrete. *Advances in Civil Engineering, 2020*, 1–10. https://doi.org/10.1155/2020/3972405

Publisher's Note