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Engineering Properties and Application Prospects of Waste Rubber Tyre in Concrete Pavement Materials

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This paper aims to study the pedestrian pavement application of the green building material rubber concrete. As the majority of worn-out tyres are discarded in landfills in large masses, the looming threat over the environment is becoming more tangible. The "black pollution" waste tire rubber is mixed into the concrete, which not only solves the problem of black pollution, but also provides a new concrete material that is more resistant to cracking than the current concrete pavement for road construction. In order to study the applicability of rubber concrete pedestrian pavement, this paper uses the axial compressive strength test to measure the rubber content of rubber concrete suitable for use in pedestrian pavement. The rubber content is to replace 20 % of the volume of fine aggregate with rubber particles, and then the rubber with this mix ratio is used. Concrete flexural experiments were carried out to explore the mechanical properties of rubberized concrete. The results show that the mechanical properties of rubberized concrete meet the requirements of pavement construction, and the flexural strength is about 20 % higher than that of ordinary concrete of the same strength. In addition, the incorporation of rubber particles improves the cracking resistance of concrete as measured by early and long-term crack resistance experiments. The number of short-term cracking cracks is much smaller than that of ordinary concrete, and the long-term drying shrinkage rate is about 1/2 of that of conventional concrete. It can be seen that rubberized concrete not only meets the requirements of sustainable development, but also satisfied the mechanical and service performance of pavement construction.

1. Introduction

The rapid development of urbanization is driving progress in the field of transportation, while the number of cars and scrapped car tires in today's society is also constantly increasing. The continuous elimination and replacement of automotive tires have led to a sharp increase in the quantity of waste tire rubber, making the disposal of waste rubber tires a widely concerned environmental issue. Rubber is a type of refractory polymer elastic material that is hard to degrade naturally even over a long period of time, making it considered a difficult to treat “black pollution”. Currently, the recycling and utilization of waste tires has become a hot topic for sustainable development and environmentally friendly utilization, attracting high attention from domestic and foreign governments. The proposal of rubber concrete has brought a new solution for the disposal the troubles (Topçu, 1995). Due to the high demand for concrete material, it not only solves the problem of black waste but also saves the extraction of natural aggregates from the perspective of sustainable development, which achieves a win-win effect.

The concept of rubber concrete, a new environmentally friendly building material, was first proposed in the last century, and foreign scientists have studied the mechanism from micro cracks to ultimate failure (Eldin and Senouci, 1993). In terms of the material itself, adding rubber into concrete causes a decrease in the compressive strength (Tian et al., 2020). Compared to natural aggregates in traditional concrete, rubber particles have a smaller elastic modulus and form weaker areas inside the concrete (Angelin et al., 2020). The interfacial bonding behaviour between rubber particles and surrounding matrix is weak, leading the rapid development of internal cracks along the weak interface inside the concrete under load (Taha, 2008). The advantages of rubber concrete lie in the light self-weight, good elasticity, durability, impact resistance, and seismic resistance, as well as its better performance in insulation and noise reduction compared to ordinary concrete (Aslani et al., 2018). Rubber

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concrete has the potential to be widely used in building materials. In practical life, road surface cracking is one of the factors limiting the service life of pavement concrete, hence the most important requirement for the performance of pedestrian is the cracking resistance. Rubber is an elastic material, that can theoretically alleviate certain shrinkage stress during deformation, extend the initial cracking time, and reduce the occurrence and development of cracks.

This article aims to explore the feasibility of using rubber concrete for pedestrian pavement construction by investigating the mechanical and servicing properties of rubber concrete. Nowadays, there are very limited examples of applying rubber concrete to the construction field, while a large number of studies have demonstrated the potential of rubber concrete in seismic structural applications (Ozbay et al., 2011). In addition, due to the addition of rubber material, the elasticity of concrete itself increases, which provides higher comfort compared to ordinary concrete pavement. The requirements for mechanical strength of pedestrian pavement materials are more tolerant than building structures, but with strict durability. Applying rubber concrete to pedestrian roads can not only utilize its outstanding durability and crack resistance characteristics, but also avoid the limitations of its low strength in practical applications. The innovation of this article is to leverage its advantages to weaken its disadvantages, with the aim of effectively solving the problem of black pollution while further exploring the performance of rubber concrete.

2. Material preparation

In general, the target strength of concrete used for pedestrian pavements is around C30. In order to design rubber concrete that meets the mechanical performance requirements, this experiment first designed the volume replacement amount of rubber particles in different situations, and tested their axial compressive strength individually. The volume fractions of rubber substitute aggregates in this experiment are 10 %, 20 %, 30 %, and 40 % (represented by R10, R20, R30, and R40, respectively). Figure 1 shows the aggregate components of rubber concrete. The ordinary Portland cement P.O. 52.5 is applied in this investigation. Coarse aggregate is natural stone with a size of 5-10 mm, and the fine aggregate is river sand with a size of 0-5 mm. The four types of rubber particles used in the experiment have sizes between 0-5 mm, which are all replaced natural fine aggregate particles. Since the mechanical properties of replacing fine aggregate with rubber particles are higher than that of replacing natural coarse aggregate (Su et al., 2015). Rubber particles were step used with sizes. Due to the fact that the addition of rubber would result in lower strength than the original concrete, the ordinary concrete sample without rubber used for comparison and reference was prepared with an expecting strength of 60 MPa (represented by R0). This study also prepared ordinary concrete with a strength of 30 MPa for reference, and the cement used for the experiment was P.O. 42.5 model. Table 1 lists all the concrete mix used for the experiment.

Figure 1: Displace of rubber concrete composition materials

Table 1: Concrete mix design

Material		R0	R10	R20	R30	R40	C30*
Cement (P.O.52.5/P.O.42.5*）		383	383	383	383	383	350
Silica fume		67	67	67	67	67	0
Fine aggregate (0-5 mm)		760	681	602	524	445	645
Coarse aggregate (5-10 mm)		977	876	774	673	572	1,240
Rubber	0-0.5 mm	0	6.0	12.0	18	24	0
	0.5-0.8 mm	0	6.0	12.0	18	24	0
	1-2.5 mm	0	18	36.0	54	72	0
	2-4 mm	0	24	48.0	72	96	0
Superplasticizer		7.6	7.6	7.6	7.6	0	0
Water		157.5	157.5	157.5	157.5	157.5	192.5
Water-cement ratio		0.41	0.41	0.41	0.41	0.41	0.55

3. Mechanical properties of rubber concrete

The compressive and flexural strength are two significant mechanical properties to define the bearing capacity of a specific material. In this study, these two tests were conducted to evaluate the performance under loading of the designed rubberized concrete material.

3.1 Compressive strength test

The size of the specimen used for tests is standard 150mm × 300mm cylindrical specimen. Prepare 3 specimens for each group of concrete, demould them at the second day after casting, and place them in a water bath for 28 days. High-strength mortar is used to fill the bottom of the rubber concrete specimen to ensure that the bottom is uniformly stressed during the compressive test. The 28-day compressive strength of the above concrete measured through experiments has been averaged by three samples and listed in Table 2.

Table 2: 28-day compressive strength of each type of concrete

Material	Strength（MPa）
R0	66.3
R10	41.3
R20	35.6
R30	28.4
R40	21.9
C30	30.0

3.2 Flexural strength test

To study the flexural strength of rubber concrete, this study used the size of 100 mm × 100 mm × 400 mm experimental specimens. According to the 28-day compressive strength results, mix design of R20 and C30 are selected as the experimental subject, and three testing samples were made for each concrete. This experiment adopted the four-point bending test method, and used a hydraulic servo loading system for loading. The flexural strength is calculated by Eq(1) based on the maximum loading force (F) obtained through testing.

$$f_t = \frac{Fl}{bh^2} \tag{1}$$

where, l represents the span between supports of 300 mm, b represents the cross-sectional width of the specimen of 100 mm, and h represents the cross-sectional height of the specimen of 100 mm. The maximum loading capacity of R20 and C30 are 15.23 kN and 12.82 kN individually, and the flexural strength are calculated as 4.57 MPa and 3.85 MPa consequently. The flexural strength of both concrete meets the construction requirements of pavement concrete. From the experimental results, it can be seen that the bending strength of rubber concrete is slightly higher than that of ordinary concrete. Under the same compressive strength, the bending strength of rubber concrete is increased by 20 % compared to ordinary concrete. This shows that the addition of rubber improves the tensile performance of concrete. Although rubber particles are the weakest part of concrete in terms of their own strength, the toughness of rubber particles can offset the stress concentration at the interface transition zone in some concrete bodies. The local stress borne in the interface transition zone is dispersed, and the flexural strength of rubber concrete will be correspondingly improved.

4. Serviceability properties tests

In order to meet the serviceability requirements, it is significant to ensure the service life of rubber concrete pavement. This study compared the deformation resistance of rubber concrete and the normal concrete pavement in both vertical and horizontal direction. The settlement test was used for detecting the changes in the vertical direction of materials after prolonged external action and the early-aged cracking test was applied for observing the occurrence and development of cracks in concrete surface with a short term.

4.1 Road settlement test

To study the deformation of rubber concrete pavement slabs, this study compared the deflection of rubber concrete and ordinary concrete within half one year. This study simulated a section of 3 m × 5 m × 0.02 m road surface in outdoor environment to measure the settlement changes of the road surface. The whole research programme is that on the 0th day after casting, the plastic film is covered on the surface for curing, then the plastic film is removed since the first day to allow it to be hardened under natural state for 7 days without loading, and after the seventh day, heavy objects were applied to the concrete surface for simulating the real pavement. As Figure 2 shows, 50 kg cement buckets were evenly placed on the concrete pavement since the 7th day to replace the pedestrian in practice. The weight and relative position of all heavy objects on the two slabs are identical for controlling variable.

Figure 2: Experimental road surface

8 detection points were settled to detect changes in concrete settlement, and take the average value as the experimental result. The measurement method is shown in Figure 3, place two identical 3-meter rods on the ground and mark the specific position of the guiding ruler to support the digital depth gauge for depth measurement. The settlement changes of the road surface at each detection point were recorded on days 14, 21, 28, 60 and 180 after pouring, respectively. The averaged measurement results are plotted in Figure 4, it can be seen that compared with rubber concrete pavement, the settlement change of ordinary concrete road is more obvious, which indicated the settlement change is more stable or rubber concrete. The tested result showed that rubber concrete pavement has a higher stability than ordinary concrete, and the average settlement value is slightly lower than that of ordinary concrete pavement.

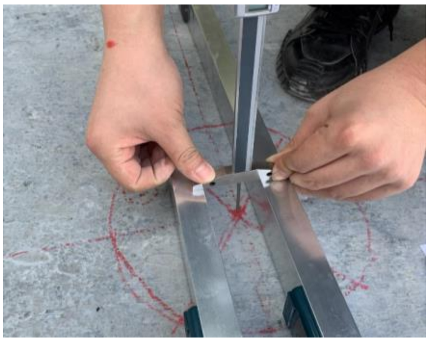

Figure 3: Measuring approach for road settlement

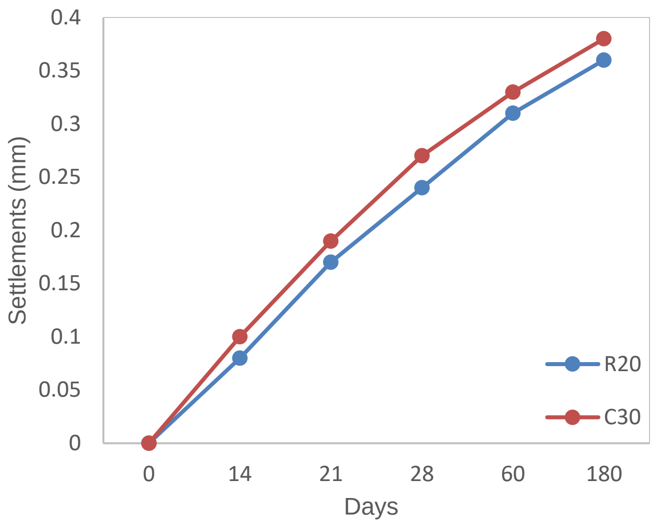

Figure 4: Average settlement changes

4.2 Crack resistance test

To ensure the stability, safety, and usability of the structure, the generation of cracks can lead to a reduction in the service life of concrete. Cracking resistance is an important indicator of whether concrete pedestrian pavement materials can be applied in practice. This study applied an 800 mm*600 mm*100 mm steel square mold with a plate edge to reflect the early cracking resistance of concrete. The basic principle is to induce the cracking of the tested concrete material using 7 parallel and flat cutting edges in the flat plate test mold, accelerating its early cracking. The operation is that the plastic film is removed after two hours pouring and using a fan to blow the two concrete surface separately to accelerate its cracking. According to the early cracking evaluation criteria of the specimen, record the cracking time, number, length, and width of cracks. Then calculate the average cracking area, number of cracking cracks per unit area, and cracking area of cracks by Eq(2), Eq(3), and Eq(4):

$$a = \frac{1}{2N}\sum_{i}^{N} W_i L_i \tag{2}$$

$$b = \frac{N}{A} \tag{3}$$

$$C = ab \tag{4}$$

where, W_i is the maximum width of the i-th crack, L_i is the length of the i-th crack, N is the total number of cracks and A is the area of the flat plate. According to four early cracking evaluation criteria: 1. Only very fine cracks; 2. Average crack area < 10 mm^2; 3. The number of cracks per unit area is less than 10 per m^2; 4. The total crack area per unit area is less than 100 mm^2/m^2, the crack resistance is divided into five levels: Level 1: All four conditions are met; Level 2: Meet three of the above four conditions; Level 3: Two of the above four conditions are met; Level 4: Meet 1/4; Level 5: No one is satisfied. The entire experiment lasted for two days, and the crack length and number of both ordinary concrete and rubber concrete slabs were marked in Figure 5. The presented results showed the cracking areas of C30 is much more than R20, which can be concluded that the addition of rubber particles exerts positive influence on the cracking resistance. The reason should be the good elasticity of rubber material delayed the generation and diffusion of cracks. By recording and processing experimental data, the early cracking results of rubber concrete and ordinary concrete is shown in Table 3.

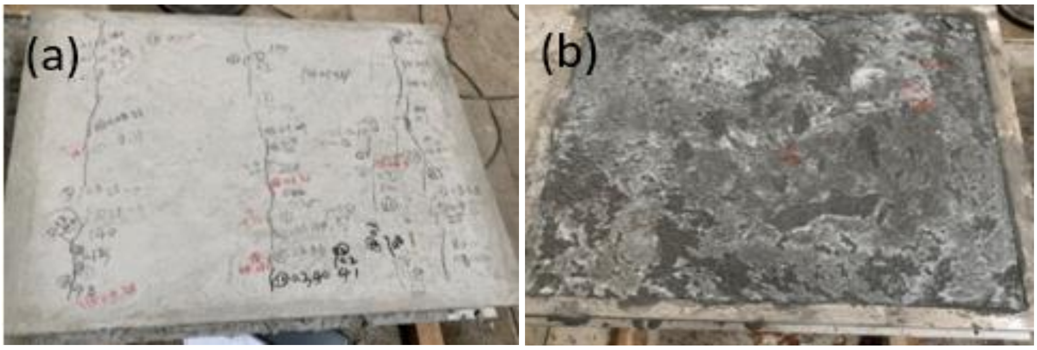

Figure 5: Early cracking results of ordinary concrete (a) and rubber concrete (b) slabs observed at 48 hours

Table 3: Early-aged cracking results

Number	Initial crack time (h)	N (per)	Maximum crack length (mm)	a (mm^2)	b (per/mm^2)	C (mm^2/m^2)	Level
R20	24	3	31.3	3.09	6.25	19.31	1st
R0	2.08	37	380	7.33	77.08	565.0	4th

5. Conclusion

This article studies the road performance of rubber concrete pavement, including mechanical and serviceability properties. Through experimental research, it was found that the compressive strength of rubber concrete meets the requirements of road construction when the volume replacement rate of rubber is 20 % to replace fine aggregate. The flexural strength of rubber concrete under this mix ratio meets the requirements of road construction, and is nearly 20 % higher than that of ordinary concrete with the same compressive strength. From the perspective of mechanical properties, rubber concrete is suitable for application in road construction. Road cracking is one of the important reasons for the failure of concrete pavement. In order to meet the requirements of concrete pavement use, this article studies the serviceability properties of rubber concrete from two aspects: surface settlement and cracking resistance. The settlement testing results indicated the addition of rubber particles alleviated road settlement, which potentially extended the service life. From the early cracking test results, it can be seen that the crack resistance of rubber concrete is level 1, which is much higher than the ordinary concrete slabs of level 4. The results demonstrated crack resistance performance has been significantly enhanced. In conclusion, this study demonstrates the feasibility of the application of rubber concrete pedestrian pavements, and proposed a new approach to manage the huge amount of waste tire rubber in a sustainable way.

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