

# Performance of Concrete with Recycled Epoxy Plate Waste as a Partial Replacement for Fine Aggregates

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**Abstract:** *The waste recycling of epoxy resin-based fiber reinforced plastics is an important topic of current environmental protection. This work investigated the potential engineering benefits of applying simply crushed recycled epoxy resin-based fiber reinforced plastic in structural concrete. In this paper, the mixing and mechanical properties of concrete products with crushed and recycled waste epoxy plates instead of some fine aggregate were studied experimentally. Three kinds of recycled crushing materials with different particle sizes below 4mm, 4mm to 9mm, and 9mm were used to prepare 10 groups of concrete samples with different proportions by replacing sand with 5, 10, and 15% volumes, respectively. The results showed that the density of the recycled plastic concrete was reduced and the slump of the concrete was increased, with the increase of the recycled crushing materials, and the mechanical properties of concrete were improved within the 5%-10% admixture, and the best results of comprehensive mechanical properties were achieved when the admixture was 10% and the particle size was 4-9mm. These results indicated that it is feasible to replace concrete fine aggregates with recycled crushing materials of waste epoxy plate, and this study not only explores a new way to recycle waste epoxy resin-based fiber reinforced plastic, but also reduces the over-exploitation of sand natural resources, which have a high social and economic value.*

**Keywords:** concrete, Epoxy plate(EP), compressive strength, tensile strength, recycling

## 1. Introduction

In the last few decades, plastic has welcomed a wide range of applications as socio-economic development has taken place. In 2016, a total of 335 million tones of plastic were produced worldwide. According to statistics, only 31.1% of this plastic waste was recycled, 27.3% was landfilled and the remaining 41.6% was used for energy recovery. In China, the production of plastic has increased annually, from 10 million tones in 2000 to 76.03 million tones in 2020, which maintains a high growth rate. The extensive use of plastic has also resulted in an increase in plastic waste, with China producing up to 63 million tones of plastic waste in 2019, but recycling only 30% of it, which is a low resource utilization rate. The global production of plastic is expected to increase to 771 million tones by 2035 and triple by 2050 [1], so there is no time to lose in recycling plastics.

To solve the plastic recycling problem, researchers have focused on the field of architecture, especially in concrete [1]. Concrete is a mixture of cement, water, and aggregates, which is widely used in construction because it is inexpensive and the material obtained performs well in terms of mechanical properties and durability after forming. However, in recent years, because of the over-exploitation of river sand, river sand resources have become increasingly tight, and the fine aggregate in concrete is in urgent need of substitutes, so it is a new way to solve the waste of resources and protect the environment by crushing waste plastics into recycled materials instead of river sand in concrete. It was shown that the use of plastic concrete can save 820 million tones of sand every year [2], which can effectively alleviate the shortage of sand resources. In addition, it is of research significance to add plastic to concrete, which can increase the strength and durability of pavements to a certain extent [3,4].

At present, researchers have studied the effects of the type, admixture and shape of plastic on the physical and mechanical properties of concrete. The types of plastic can be divided into two main categories: thermoplastics and thermosets [5-8]. In recent years of research on plastic concrete,

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researchers have mostly focused on thermoplastics, especially on polyethylene terephthalate (PET), polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC). Mohammed et al. [9] tested PET waste by mixing it into reinforced concrete beams. The test results showed that although the compressive strength of reinforced concrete beams was reduced with the incorporation of PET particles, he found that the incorporation of 15% PET waste did not affect the load-bearing capacity of the concrete, proving that waste PET waste can replace sand to some extent. Al-Hadithi et al. [10] concluded that the compressive strength of concrete is reduced mainly because PET waste has a smooth surface and its bond strength to cement inside concrete is not as effective as that of river sand. Zehil G P et al. [11] explored the feasibility of blending cross-linked polyethylene (XLPE) waste materials into concrete by formulating several groups of concrete mixes with different water-cement ratios for performance tests. The results showed that the density and strength of the concrete were subsequently reduced with the addition of plastic and that the permeability of the concrete was greatly improved, but he found that the strength of the concrete could be mitigated by reducing the water to ash ratio. Parra C et al. [12] replaced 48% of the aggregate with recycled lightweight aggregates (30% PP and 18.5% cork) in order to research lightweight concrete. The results showed that the compressive strength and density of the lightweight concrete mixes were each reduced, but both retained effective levels of structural use, and the porosity of the concrete was greatly improved by the increase in PP recycled material, which improved the durability of the concrete. Mohammed et al. [13] conducted tests on PVC waste instead of concrete coarse and fine aggregates in order to investigate the effect of plastic on the performance of concrete. Results of the tests showed that when PVC waste is used instead of concrete aggregates by no more than 30%, the loss of compressive and tensile strength does not exceed 8%, and the wear resistance of the concrete is improved, which shows that plastic concrete has some application value.

It has been found through existing studies that for PET, PVC and other such common thermoplastics, most studies have confirmed that the compressive and tensile strengths of concrete are inevitably reduced by the incorporation of plastic, but will improve the workability of concrete, and some researchers have shown that by choosing the right amount of substitution or improving the water-cement ratio of concrete [11], the value of plastic concrete will be increased. It is worth noting that thermoplastics is a very valuable material that can be recycled by melting due to its inherent properties. Nevertheless, thermosetting plastics are not easy to be heated and melted, which makes it difficult to be crushed and recycled by conventional methods [14,15]. In recent years, there are few researches on thermosetting plastic concrete, most of which focus on such common materials as PU (polyurethane), Melamine, etc. Mohammadian et al. [16] investigated melamine waste. They used a grinder to grind melamine waste to obtain recycled materials, and made five groups of samples to compare with Panyakapo's method. The results showed that melamine waste resulted in a decrease in the density and compressive strength of concrete. In addition, it was found that the porosity and water absorption of concrete increased, and it was concluded that melamine aggregate could be successfully used in non-load bearing lightweight concrete. Tantisattayakul et al. [17] explored the feasibility of mixing waste polyurethane foam into concrete. The research showed that it was feasible to add recycled thermosetting plastics to concrete instead of aggregate, which mainly meet the requirements of non-bearing concrete and was a resource efficient and less dangerous choice. Therefore, it is great interest to investigate thermosetting plastic waste as an aggregate for concrete.

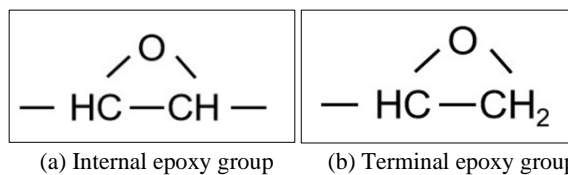
There are conventional thermosetting plastics such as phenolic resins (PF), polyurethane (PU), epoxy resins and other unsaturated resins. In particular, epoxy resins are widely used in aerospace, sport, marine, civil engineering, chemical, automotive and offshore industries because of its high durability, high strength, chemical resistance and corrosion resistance [18]. Epoxy resin-based glass fibre reinforced plastics are used extensively in the energy and electrical sectors, for example in wind turbine blades, epoxy resin sheets etc. Waste plastics are manufactured through a simple crushing process to create recycled materials and replace fine aggregates, which not only can be obtained as a new concrete conforming material in the construction field, but also have a high economic value. In this paper, the waste EP is crushed into recycled crushing materials (RCM) with different particle sizes, and then it is

added to the concrete with different dosage and equal volume instead of fine aggregate. Finally, the physical and mechanical properties of the concrete products are tested, including density, slump, compressive strength and splitting tensile strength. At the same time, the microstructure of the concrete products is analyzed. A new type of recycled plastic concrete with better comprehensive performance is obtained, which not only has certain economic value, but also can solve the environmental problems caused by the waste thermosetting plastics.

## 2. Materials and methods

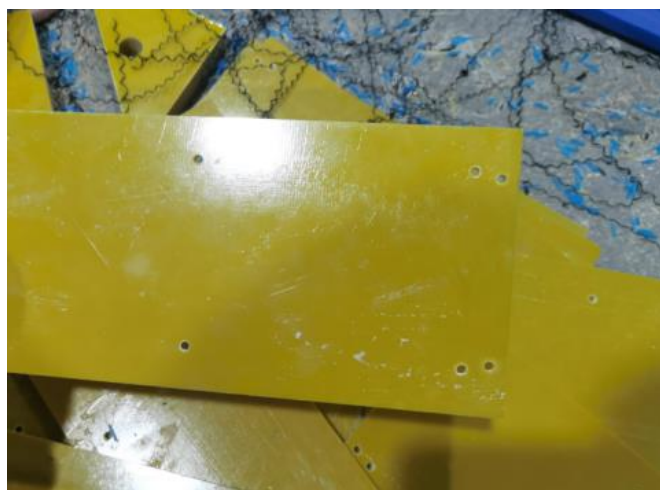
### 2.1. Epoxy plate

Epoxy resins are one of the common thermosetting polymers. It has internal epoxy groups, as shown in Figure 1.



**Figure 1.** Chemical structure of the epoxy group

With its low price, epoxy resins have become an indispensable insulating and dielectric material today, including laminated circuit plates, structural fibre-reinforced composites, electronic component encapsulation and adhesives. In particular, fibre-reinforced epoxy composites account for 18% of the global epoxy resin market [19]. The object of study for this experiment was 3240 laminated glass cloth made of epoxy resin emulsion, which was supplied by Guangzhou Hongxin Insulation Material Co., Ltd, with a thickness of 3 mm, as shown in Figure 2. The plate is an epoxy resin composite material that is manufactured by glass cloth being fully infiltrated into the epoxy resin matrix, and then being prepared through a moulding process such as baking and hot pressing. Because it has good insulation and mechanical properties of epoxy resin, it is widely used in industries such as electrical and electronics, with specific parameters as shown in Table 1.



**Figure 2.** Epoxy plate scraps

**Table 1.** Performance of epoxy plate

Project	Result
Density (kg/m <sup>3</sup> )	1982
Water absorption (%)	0.05-0.095
Elasticity modulus (MPa)	1.53×10 <sup>4</sup>
Shearing strength (MPa)	28-50.7
The load deformation temperature (°C)	215

Bond strength (KN)	3.594
Tensile strength (MPa)	127-165
Shrinking percentage (%)	0.1-0.4

Consider that EP is a composite of epoxy resin and glass fibres. The effect of the fibres also needs to be considered when conducting concrete tests. It is useful to mention that much of the current literature shows that fibrous materials contribute to the strength of concrete. For example, Kassimi et al [20] used four types of fibres (steel, two types of polypropylene, and blended fibres) reinforcement, blended into concrete at 0.3 and 0.5% by volume, respectively, in order to assess the ability of fibres to be used as a repair material for reinforced concrete beams. The test results showed that the fibre concrete was able to successfully restore the load resistance of the specimens and is of high value in the repair of infrastructure. A similar study was carried out by Aslani et al [21]. They mixed different volume fractions of polypropylene and steel fibres into concrete. The results showed that the best performance of the concrete was obtained when the volume fraction of polypropylene fibres was 0.1% and the volume fraction of steel fibres was 0.75%, with some improvement. Chen, M et al [22] investigated the feasibility of incorporating fibrous polymers made from waste tyres into concrete. The results showed that the flexural strength of the recycled concrete increased by 3.6% to 9.6% and that the recycled concrete had the longest fatigue life when blended at 4.8 kg/m<sup>3</sup>. Kim, J.S et al [23] studied the enhancement of mechanical properties of concrete by jute fibres. The results showed that jute fibres could be successfully used in concrete with a high improvement in strength properties. Ahmad et al [24] blended glass fibres and nylon into concrete in different proportions. The results showed that the toughness and modulus of elasticity of the concrete were increased by the addition of glass fibres and that the water absorption and the void fraction of the concrete were slightly increased as the amount of fibres was added. Whether natural fibres, plastic fibres or glass fibres, fibrous materials have a positive effect on concrete, and most studies have shown that the ductility of concrete was enhanced because of the fibres, which also had a definite effect on the strength improvement of concrete. In order to reduce costs, this study did not separate the fibres separately, the EP was crushed mechanically and the RCM was added directly to the concrete, and the crushing equipment was supplied by Changzhou Lixiong Machinery Manufacturing Co., Ltd. The specific parameters of the RCM are shown in Table 2.



**Figure 3.** Mechanical comminution process

**Table 2.** RCM performance parameters

Name	Size (mm)	Apparent density (kg/m <sup>3</sup> )	Bulk density (kg/m <sup>3</sup> )
Ea	4-9	1565	801
Eb	<4	1358	374
Ec (mass ratio a:b=1:1)	<9	1462	510

## 2.2. Mix design and testing procedures

The test was carried out using P.O42.5 grade ordinary silicate cement, made in China, Anhui Yingpu Jinlong Co., Ltd. River sand with a fineness modulus of 2.7, made in China, Anhui Pingping Sandstone Sales Co., Ltd. And granite stones with a grain size of 5 to 20 mm (manufactured by Huishan Natural Granite Factory, Fuling Town, Jixi County, Anhui Province). The mix ratio was adjusted according to the C35 concrete and the design method was based on compressive strength. The test program was specifically designed as follows: Ea, Eb and Ec were mixed into the concrete, replacing sand at 5%, 10% and 15% by volume, respectively. A set of comparative tests was designed, numbered M0. A total of 10 sets of tests were carried out in this test, and in order to minimize the effect of test errors, three 100 mm × 100 mm × 100 mm specimens were made in each set for testing the compressive strength and splitting tensile strength. Specific fits are shown in Table 3.

Due to the low density of RCM, it is prone to agglomeration during preparation, and if agglomeration and bunching exist, the composite cannot be used in actual production [25]. Therefore, for the correctness of the test results, a fine dispersion of RCM in the concrete was made possible. In this test, the RCM was first mixed evenly with cement, sand and stone, and then water was slowly added several times. After the concrete was mixed, it was first tested for apparent density and slump. Immediately after the test, the mould was filled and the numbered concrete specimens were placed in a standard curing room at a temperature of (23±1)°C and humidity of more than 95%. After 24 h, the moulds were demoulded and the demoulded specimens continued to be placed in the standard curing chamber until they had been cured for the specified periods (7, 14 and 28 days), then the specimens were removed, dried and tested for mechanical properties using a Sanshi press manufactured by Shanghai Sanshi Zongheng Machinery Manufacturing Co., Ltd.

**Table 3.** Mix table of EP concrete with different EP content and particle size

Number	Water (kg/m <sup>3</sup> )	Cement (kg/m <sup>3</sup> )	Sand (kg/m <sup>3</sup> )	Stone (kg/m <sup>3</sup> )	EP		
					Name	Ratio (%)	Content (kg/m <sup>3</sup> )
M <sub>0</sub>	185	420	581	1235	/	/	/
M <sub>a-5</sub>	185	420	552	1235		5	17.23
M <sub>a-10</sub>	185	420	523	1235	M <sub>a</sub>	10	34.46
M <sub>a-15</sub>	185	420	494	1235		15	51.69
M <sub>b-5</sub>	185	420	552	1235		5	15.00
M <sub>b-10</sub>	185	420	523	1235	M <sub>b</sub>	10	30.00
M <sub>b-15</sub>	185	420	494	1235		15	45.00
M <sub>c-5</sub>	185	420	552	1235		5	16.15
M <sub>c-10</sub>	185	420	523	1235	M <sub>c</sub>	10	32.30
M <sub>c-15</sub>	185	420	494	1235		15	48.45

## 3. Results and discussions

### 3.1. Apparent density of concrete

Figure 4 shows the test results for the different groups of apparent densities. As shown in Figure 4, the apparent density of concrete was reduced with increasing proportions of EP, and the reduction in apparent density was greater in the M<sub>b</sub> group than in the M<sub>a</sub> and M<sub>c</sub> groups, mainly because the apparent density of Eb was lower than Ea and Ec when compared to the other two groups. In addition, the higher number of pores being introduced due to the RCM being incorporated into the concrete also contributes to the reduction in apparent density, as shown in Figure 5. As the RCM was increased, the rate of change in the apparent density of the EP concrete began to increase, probably because, compared to river sand, the epoxy resin and the fibres themselves were less absorbent, resulting in poorer water retention and therefore higher rates of change of the apparent density of the concrete.

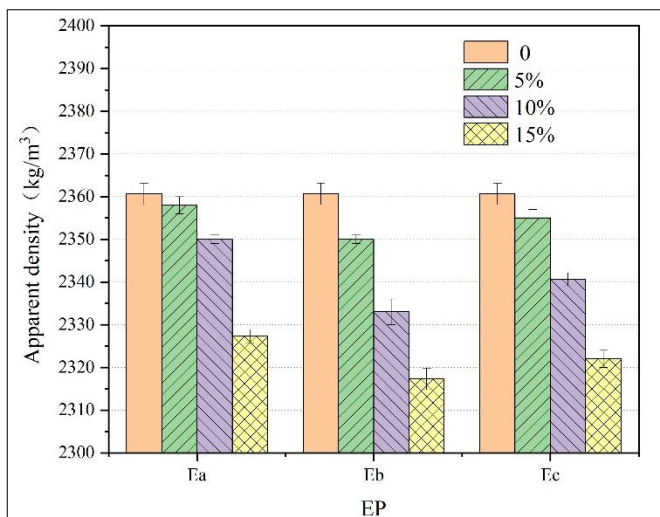


Figure 4. Apparent density of EP concrete

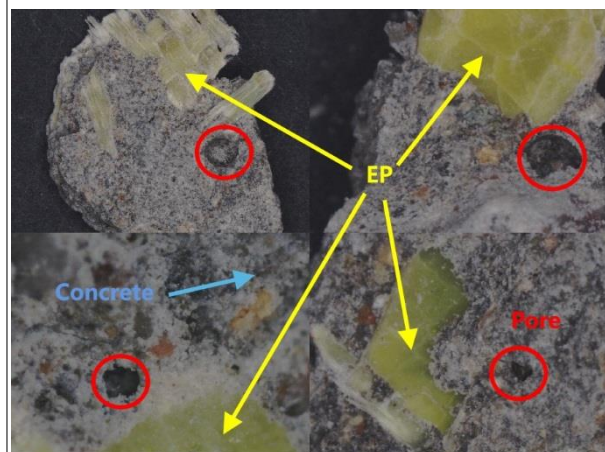


Figure 5. EP concrete internal pore

### 3.2. Slump of fresh concrete

Slump is an important indicator of the workability of concrete and the requirements for slump vary in different construction scenarios. Its degree directly reflects the plasticity of the concrete mortar and its pumpability. The test results of the EP concrete slump are shown in Figure 6. The error bar in the figure represents the mean error. It can be seen from the figure that the slump of concrete gradually increases with the increase of RCM. Compared with  $M_0$ ,  $M_{a-5}$ ,  $M_{a-10}$  and  $M_{a-15}$  increased by 15.38%, 46.15% and 107.7%, respectively.  $M_{b-5}$ ,  $M_{b-10}$  and  $M_{b-15}$  increased by 53.85%, 92.31% and 123.1%, respectively.  $M_{c-5}$ ,  $M_{c-10}$  and  $M_{c-15}$  increased by 38.46%, 61.54% and 100%, respectively. The workability of EP concrete was improved, a result that was consistent with the studies of Silva, R. V. et al [26], the main reason for this phenomenon being that both the epoxy resin and the fibres themselves have a smooth surface, so that in mortar, their flowability is improved.

The amount of slump variation in  $M_b$  was higher than that in  $M_a$  and  $M_c$  groups, mainly because, the larger particle size epoxy resin and fibres were formed into a network structure inside the mix [27], thus inhibiting the segregation and flow of the mix. As showed in Figure 7, SEM showed that the distribution of RCM in EP concrete is disordered. When the content of RCM was more than 10%, the water retention of mortar became worse and the fluidity increased.

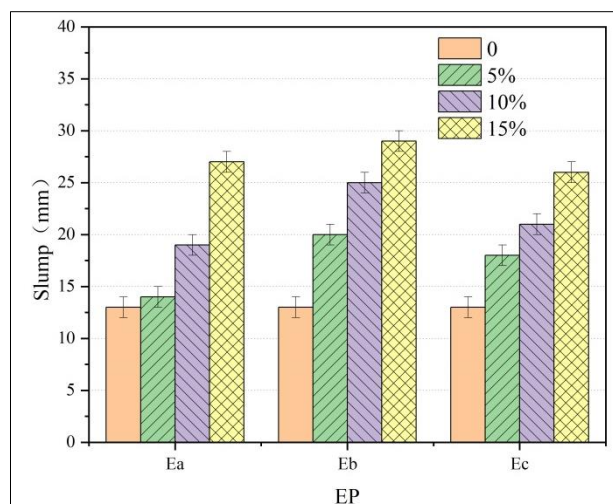


Figure 6. Slump values of fresh concrete

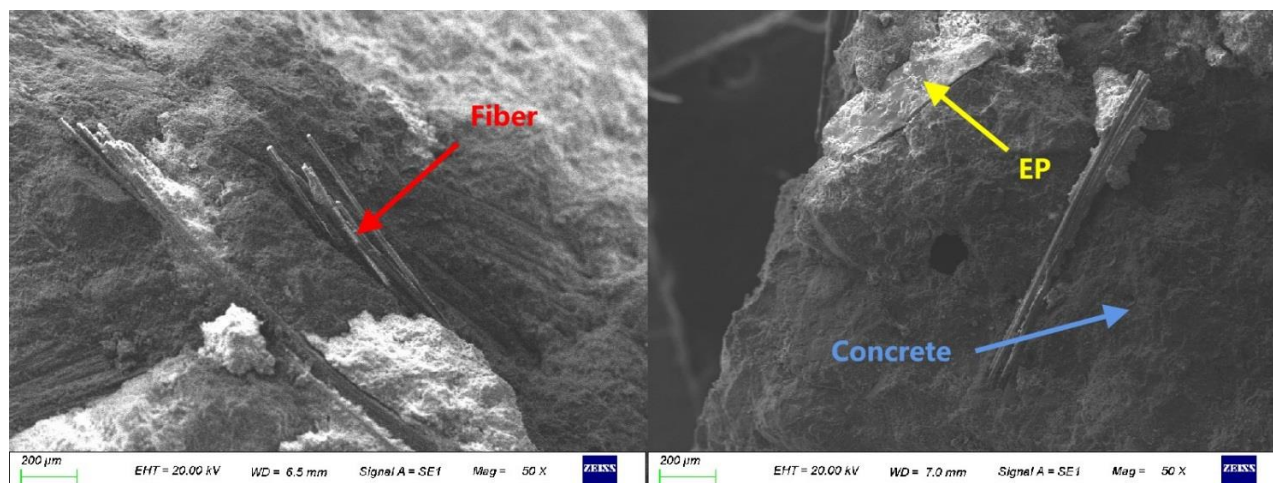


Figure 7. SEM of EP concrete

### 3.3. Compressive strength

Compressive strength is one of the most basic mechanical property indicators in the study of concrete materials and one of the most important design indicators for structural design. It not only reflects the strength grade of the concrete material, but also affects the performance indicators of concrete splitting tensile, flexural, modulus of elasticity, stress-strain, etc. Figures 8-10 showed the compressive strength of EP concrete with different particle sizes of RCM at 7d, 14d and 28d. As shown in the graph, the compressive strength values of concrete showed an increase followed by a decrease as the RCM increased, and this experimental phenomenon was consistent with the research results in reference [14]. The test results showed that when the RCM was less than 10%, the compressive strength of concrete increased. For example, when the addition amount was 10%, the compressive strength values of 7d, 14d and 28d were 13.92%, 25% and 26.34% higher than M0 respectively. This is mainly because the particle size distribution of the RCM particles is more continuous and their content contributes to the filling of the sand aggregate, resulting in a lower void ratio in the mortar aggregate.

When the amount of RCM exceeded 10%, the compressive strength of the concrete mostly showed a reduction, which was caused by the hydrophobicity of the EP itself. In addition, the smooth surface of the epoxy resin and fibres makes for a weak bond with the mortar, which is also a factor in the reduced compressive strength of the concrete.

Figure 11 showed the compressive strength of the M<sub>a</sub> group and the control group at 7 days. The results showed that compared with the control group, the cracks of EP concrete were smaller and there was no obvious fragment falling off. This showed that the addition of RCM improved the ductility of EP concrete.

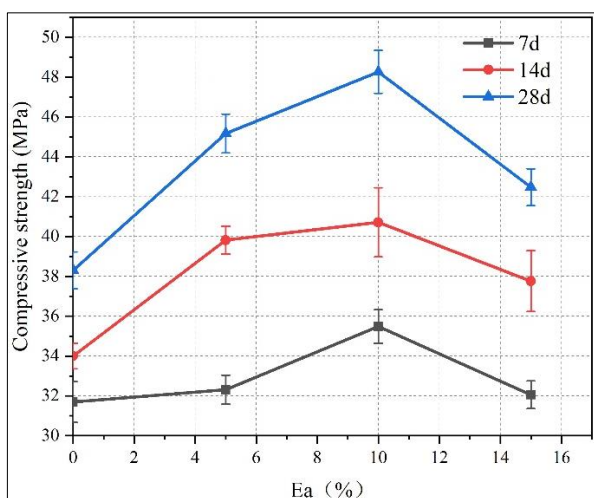


Figure 8. Compressive strength of Ea concrete

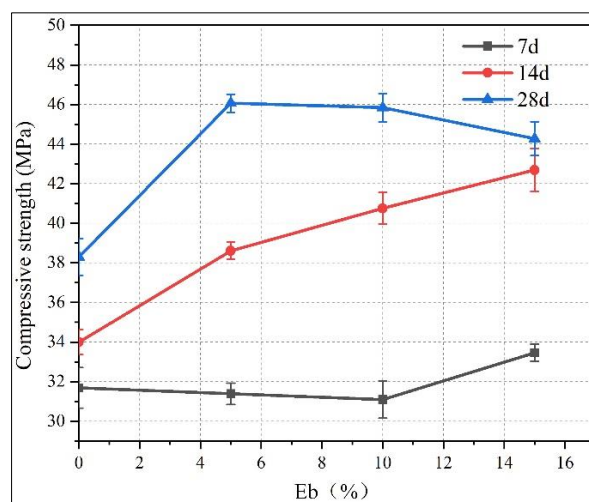


Figure 9. Compressive strength of Eb concrete

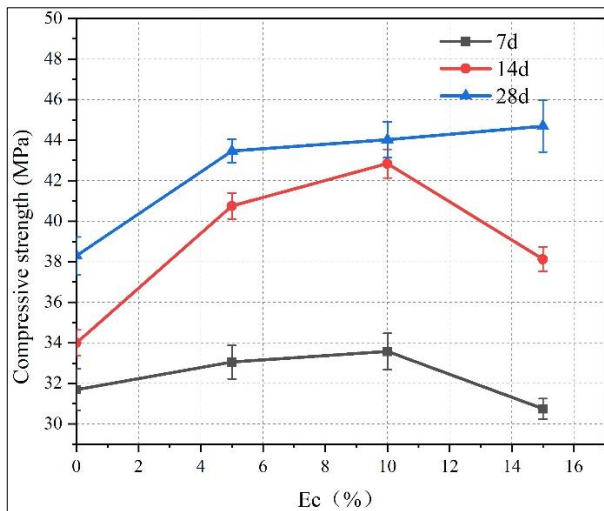


Figure 10. Compressive strength of Ec concrete

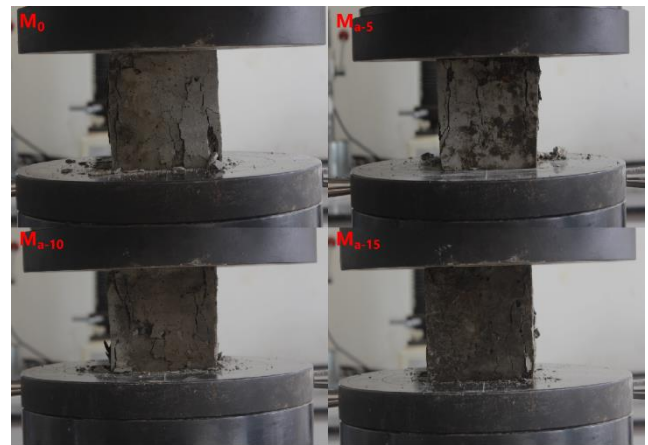


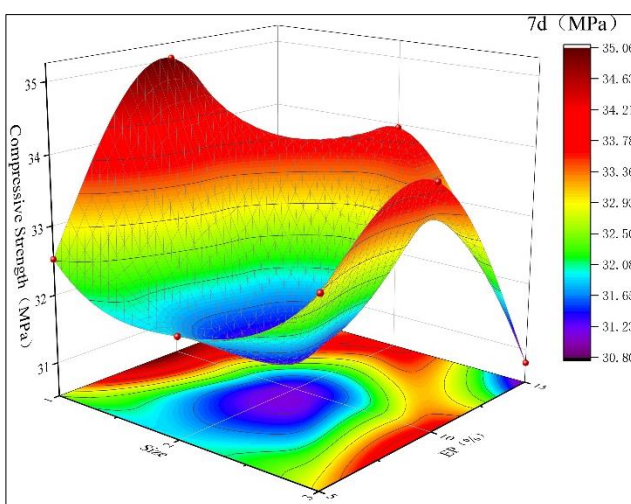
Figure 11. Compressive strength testing process

### 3.4. Analysis of compressive strength factors

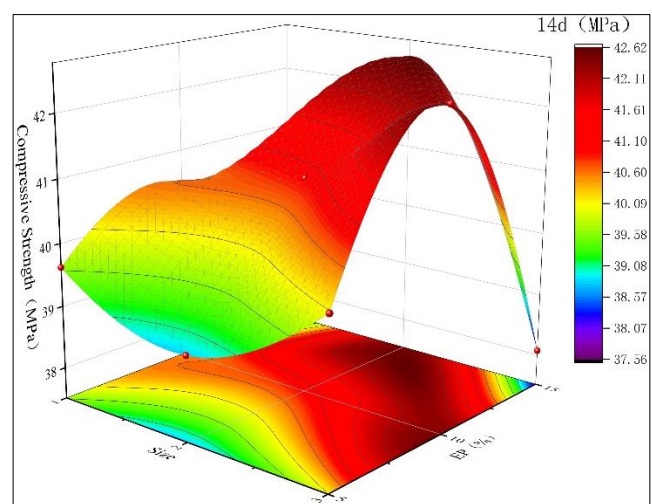
Figures 12 showed the effect of the two factors of admixture and particle size on the compressive strength of 7, 14 and 28 days, respectively, where Ea, Eb and Ec were replaced by 1, 2 and 3, respectively. In the 7 days compressive strength analysis graph, compared with the particle size of the material, the influence of the amount of admixture on the compressive strength was more significant, and the change of its response value was the largest. In the 14d and 28d analysis charts, compared with the amount of RCM, the impact of particle size on the compressive strength was more significant, and the change of response value was the largest.

The 28 days compressive strength of concrete was the key to evaluate its performance of concrete. Figure 14 showed that the compressive strength at 28 days at position 1 was the maximum at 10% of the admixture. Therefore, the maximum compressive value was obtained by selecting the mixing amount of Ea and 10%.

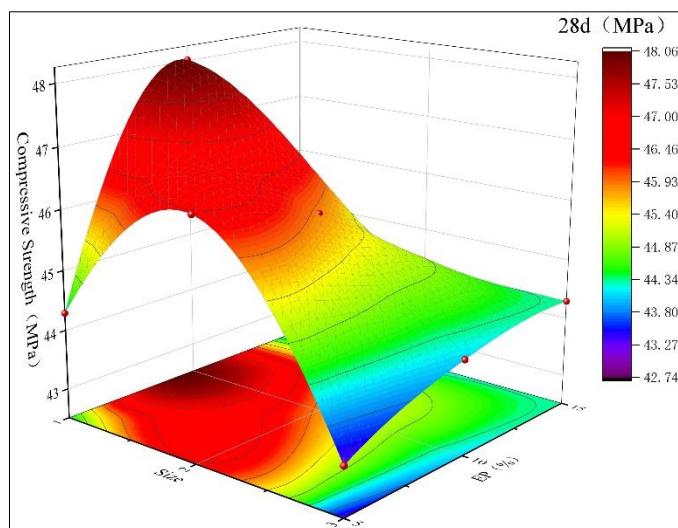
The 28 days compressive strength of concrete was the key to evaluate its performance of concrete. Figure 14



a. 7 days



b. 14 days



c. 28 days

**Figure 12.** Analysis of compressive strength factors

### 3.5. Splitting tensile strength

In the basic mechanical properties of concrete testing, tensile strength is an important parameter of mechanical properties. Tensile strength can directly reflect the structural design of concrete. In the natural state, concrete damage often occurs in tensile damage. Therefore, the measurement of the tensile strength of concrete is concerned with its limit state, is an important basis for concrete material damage and strength theory. Figures 13-15 showed the splitting tensile strength values at 7 and 14 days for different particle sizes of RCM, respectively. The graph showed that the mean values of the concrete measurements for the control group at 7 and 14 days were 3.45 MPa and 4.06 MPa, respectively. The tensile strength of group  $M_a$  concrete mixed with 5% to 15% was increased by 15.63% to 23.25% and 12.45% to 14.92% at 7 and 14 days, respectively, relative to the base concrete. The tensile strength of the concrete in the  $M_b$  group mixed with 5% to 15% was reduced by 1.23% to 4.17% and 2.02% to 4.06% at 7 and 14 days, respectively. The tensile strength of the  $M_c$  group concrete mixed with 5% to 15% decreased by 1.88% to 4.50% and 1.00% to 8.70% at 7 and 14 days, respectively.

Test data showed that the splitting tensile strength of EP concrete increased first and then decreased with the increase of  $E_a$ , and the splitting tensile strength was better than that of ordinary concrete at 5-10% admixture. The main reason was that after the concrete specimen is subjected to external load, the stress was transferred to the internal epoxy resin and glass fiber. However, due to their high strength, large particle fibers and epoxy resin prevented the expansion of macro cracks, and the splitting tensile strength of EP concrete was improved [28]. However, the tensile strength of concrete mixed with  $E_b$  is different. With the increase of the content, the splitting tensile strength of the test group was lower than that of the control group. The main reason was that due to the small particle size of crushing, the epoxy resin and fiber are separated and the mechanical properties were reduced. Therefore, it was difficult for epoxy resin and fiber to transfer test stress under test pressure. In addition, the poor interfacial connection between the epoxy and fibres and the concrete mortar was a major contributor to this result.

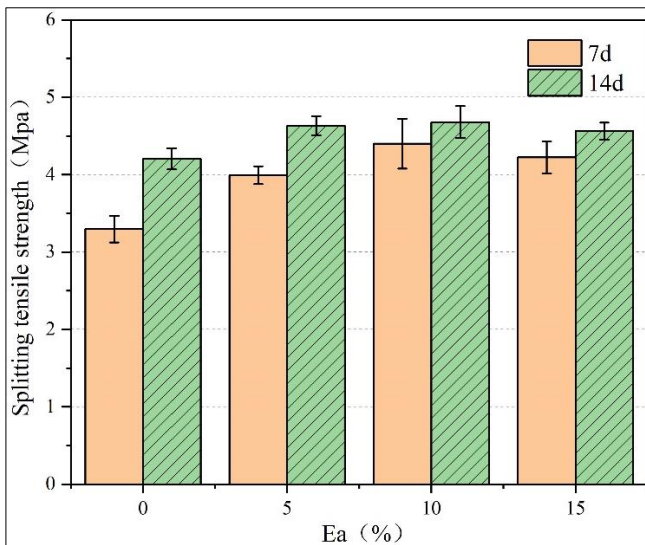


Figure 13. Splitting tensile strength of Ea concrete

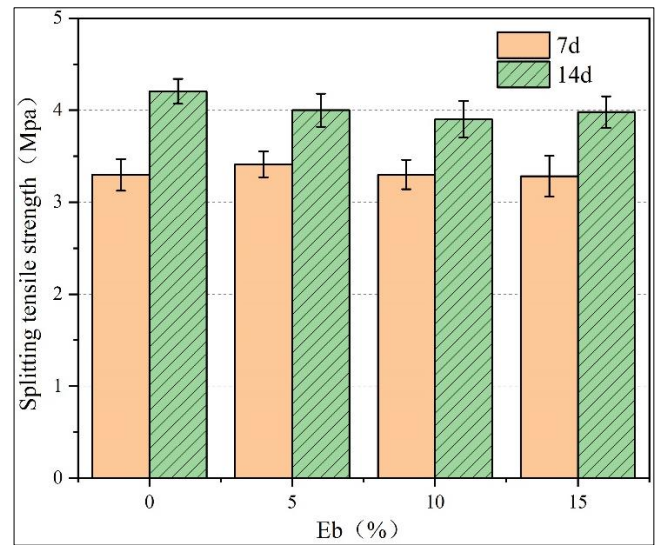


Figure 14. Splitting tensile strength of Eb concrete

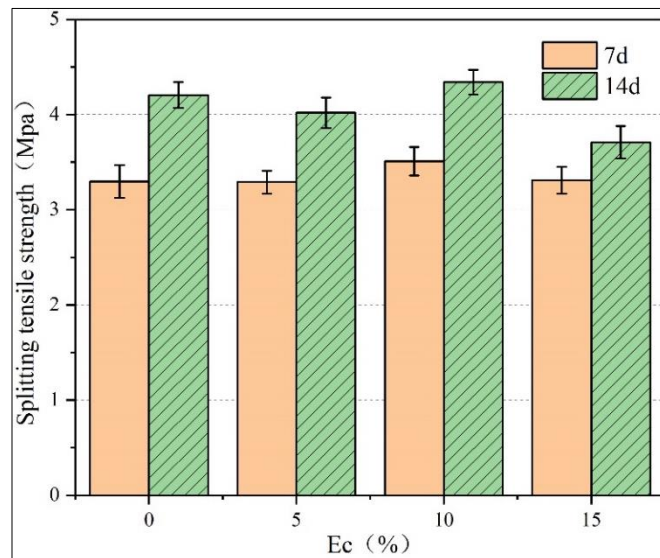


Figure 15. Splitting tensile strength of Ec concrete

### 3.6. Analysis of splitting tensile strength factors

Figures 16 showed the effect of dosing and particle size on the splitting tensile strength at 7 and 14 days, respectively. The results showed that the particle size had the greatest influence on the splitting tensile strength compared with the additional amount. When the particle size changed, the response value of tensile strength changed greatly. When the dosage was 10%, the splitting tensile strength of EP concrete at position 1 obtained the maximum value.

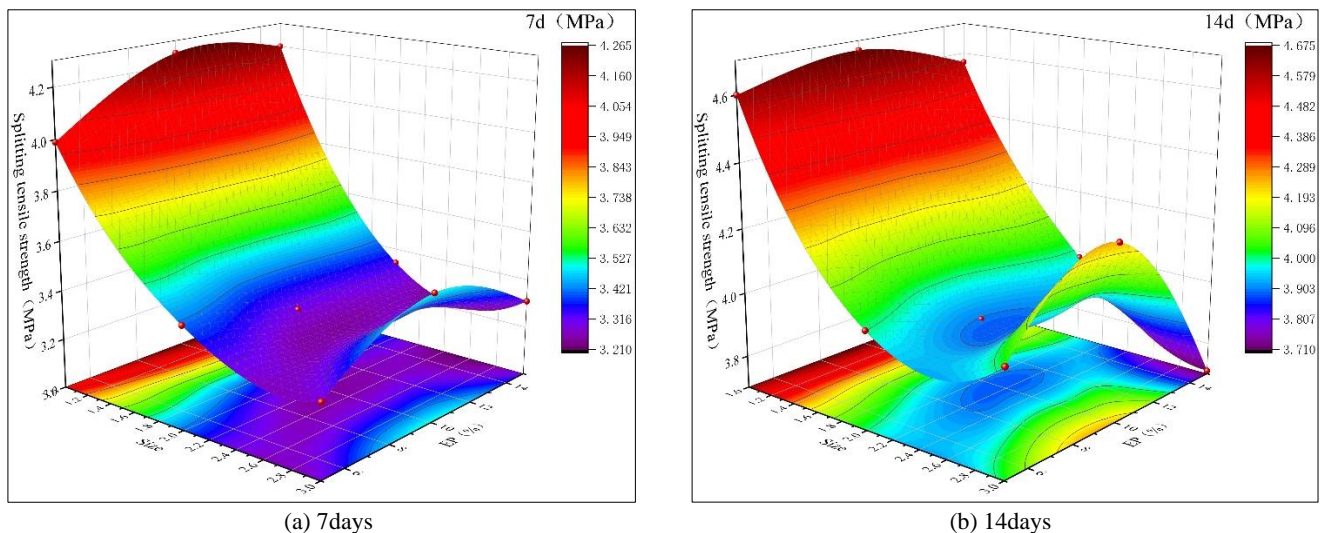


Figure 16. Analysis of splitting tensile strength factors

#### 4. Conclusions

The paper focused on the replacement of fine aggregates in concrete with RCM of different admixtures and particle sizes at 5, 10 and 15% by volume, respectively. At the same time, it analyzed the influence of the dosage and particle size on the density, slump, compressive strength, tensile strength of concrete. The results of these tests showed a reduction in density and an increase in the slump of the EP concrete compared to the control group without RCM. When the amount of 5-10% was mixed, the concrete obtained better mechanical properties and above the control group; when the amount of 10% was mixed and the particle size was 4-9 mm, the concrete had the best mechanical properties. Considering that EP concrete may be used in non-load bearing applications in the future, these properties are largely adequate for use. Therefore, it is a feasible solution to use the waste epoxy plate as fine aggregate for concrete instead of sand. It not only solves the recycling problem of the waste epoxy plate, but also saves sand and protects the environment. Based on the results and discussions in this paper, the following points can be summarised.

The apparent density of EP concrete was influenced by the amount of RCM incorporated, decreasing with increasing RCM, which was caused by the fact that the density of the RCM itself was lower than that of the sand.

In the slump test, the slump of the EP concrete was increased with the addition of RCM, mainly because both the epoxy resin and the fibres mixed within it have a smooth surface, which, together with their inherent hydrophobicity, led it to increase its slump.

The EP concrete did not show brittle damage in the compressive tests carried out. As the EP doping increased, there was an increase followed by a decrease in all groups. EP concrete showed a reduction in compressive strength, due to the hydrophobicity of EP itself. In addition, the smooth behaviour of the epoxy and fibres resulted in a weak bond with the mortar, which was also a factor in the reduction of the compressive strength of the concrete.

The splitting tensile strength of EP concrete in the tensile strength tests all showed an increase followed by a decrease as  $E_a$  increased. The splitting tensile strength was better than that of ordinary concrete at 5 to 10%. This was because when the stress was continuously loaded, the stress was transferred to the epoxy resin and fibres and the large size of the fibres hindered the expansion of the cracks, thus increasing the splitting tensile strength.

In the factor analyses of the mechanical properties test results, it was found that the particle size had the greatest effect on the tensile and compressive strengths compared to the admixture amount, and the optimum mechanical properties were obtained when the EP particle size was between 4 and 9 mm and the admixture amount was 10%.



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