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Influence of PP Fiber and SBR Latex on the Mechanical Properties of Crumb Rubber Mortar

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ABSTRACT: This article presents a new kind of rubber mortar modified by polypropylene fiber (PP fiber) and styrene-butadiene rubber latex (SBR latex). The mechanical properties of this crumb rubber mortar were investigated in the research, including the compressive strength, flexural strength, flexural toughness, and flexural elasticity modulus. The test results showed that the flexural toughness index of the rubber mortar was seen to enhance by about 50–100% with the addition of PP fiber and SBR polymer latex. Due to the addition of PP fiber and SBR latex, the flexural elastic modulus of rubber mortar could further reduce by 4–27%. The three-phase composite dispersion model of this rubber mortar was put forward. Furthermore, it was observed from scanning electron micrograph that the interfacial transition zone between the rubber particles and cement paste was enhanced by the SBR latex, and the interleaving of polymer films and rubber particles strengthen the flexibility and toughness of the mortar. © 2014 Wiley Periodicals, Inc. J. Appl. Polym. Sci. **2014**, *131*, 40591.

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INTRODUCTION

In recent years, worldwide growth of automobile has tremendously boosted tire production. This has generated huge stockpiles of used tires. It is estimated that about 1.5 billion rubber tires are manufactured in the world p.a. Recently, more than 50% of waste tires are discarded without any treatment.[1,2] Approximately 259 million tires were fabricated in the United States, although the market for the scrap tire uses around 80% of used tires in the United States; the remaining 20% is stockpiled or put in the land fill.[3] In China, the production of waste tires is increasing with an annualized rate of 15% recently; an incomplete statistic shows that the production of waste tires was nearly 0.2 billion in 2009, about 65% of the waste tires cannot get recycling or any treatment.[4–6] Because of the environmental threat associated with waste tires, their proper disposal has attracted significant attention in recent years.

On the basis of the above situation, nowadays extensive studies have been conducted on used tire rubber modified concrete and mortars. Results have indicated that rubber concrete mixtures show lower density, increased toughness and ductility, higher impact resistance, lower compressive strength, and more efficient sound insulation.[7–12] The introduction of rubber particles significantly increases the strain capacity of materials.[13–15] Rubber particles in cement paste enhance the toughness of the composite.[16,17] However, a lot of studies have indicated that the presence of crumb rubber in concrete lowers the mechanical properties (compressive and flexural strength) compared to those of conventional concrete, and this decrease in strength was found to be directly proportional to the rubber content.[18–20] The lower strength is due to the lack of bonding between the crumb rubber and cement paste.[21–23] Therefore, the poor mechanical properties of rubber concrete have significantly hampered its application in the building area.

To solve these problems, we put forward new ideas that using polypropylene fiber (PP fiber) and styrene-butadiene rubber latex (SBR latex) to fabricate compound-modified crumb rubber mortar (FPMRM). In this study, the influence of PP fiber and SBR latex on the mechanical properties of crumb rubber mortar was probed. We focus on the flexibility and toughness of this rubber mortar, in addition to its routine mechanical properties. The constitutive model of this new rubber mortar was put forward in this article. The modified mechanism of PP fiber and SBR latex on the rubber mortar was also investigated by the microscopic test. The proposed method could provide a sand source and solve the problem of sand shortages as well as recycle waste materials. This study will also benefit the

Table I. The Physical Properties of SBR Latex

Solid content (%)	pH	Viscosity at 25°(Pa.s)	Density (g/cm^3)	Mean grain size (nm)	Glass transition temperature (°)	Surface tension (mN/m)
50	8.3	40 m	1.01	150	13	45

Table II. The Related Properties of PP Fiber

Length (mm)	Diameter (mm)	Density (g/cm^3)	Melting point (°)	Ignition temperature (°)	Tensile strength (MPa)	Specific surface area (m ^{2} /kg)
9±0.2	0.025-0.045	0.91	165	172	>350	>245

application of FPMRM in screed-coat or repairing materials in building field.

EXPERIMENTAL

Materials

One kind of composite Portland cement was used in this research. The polymer used was a kind of SBR latex. The physical properties of SBR latex are shown in Table I. A type of PP fiber was used in this experiment, and the technical parameters and physical properties of the PP fiber are given in Table II. The river sand conformed to ASTM C33 specifications, its fineness modulus and apparent density was 2.50 and 2.632 g/cm^3, respectively. The particle size of waste tire rubber powder was 2.36–4.75 mm. The water used conformed to ASTM C94 for water for mortar mixing.

Test Variables

In this study, the fixed water-binder ratio was 0.60, the fixed binder-sand ratio was 1/3, the fixed volume fraction of PP fiber was 0.1%, and the fixed binding agent was 580 kg/m^3. The sands were replaced with 0, 10, 20, 30, and 40% volume fraction of waste tire rubber particles, and the polymer–cement ratio of SBR was 0, 5, 10, 15, and 20%, respectively.

Experimental Methods

The dimensions of the specimens for the compressive strength, flexural strength, flexural toughness, and flexural modulus tests were 40 × 40 × 160 mm.

The flexural toughness and flexural modulus were tested by the universal testing machine. The flexural toughness was evaluated by Japan JSCE-SF4 methods. The toughness index σ was calculated by formula (1):

$$\sigma = \frac{T_b L}{b \cdot h^2 \delta_{tb}} \tag{1}$$

In the formula, L is the beam span (mm), δ_{tb} is the deflection of L/150, h is the beam height (mm), b is the beam width(mm), T_b is the area of the load–deflection curve under the deflection of L/150.

The specimens for scanning electron micrograph (SEM) testing were obtained from the 90-day curing specimens of FPMRM; the testing specimens was dried by a vacuum and coated with a thin layer of gold before observation, and the microstructure was observed with a SU8010 scanning electron microscope.

RESULTS AND DISCUSSION

The Influence of Rubber Particles on Strength Properties of Ordinary Mortar

The influence of crumb rubber particles on the strength properties of ordinary mortar is shown in Figure 1. The flexural and compressive strength of cement mortar with 10 vol % of rubber particles were improved to a certain extent, and in a curing time of 28 days, its compressive and flexural strength arrived at 5.84 and 28.07 MPa, respectively, increased by 12.7 and 12.8% correspondingly, compared with the specimens without rubber particles. With the content of rubber particles in mortar increasing further, the compressive and flexural strength of cement mortar reduced in a large scale. The compressive and flexural strength of rubber mortar cured in 28 days with 50 vol % of rubber particles reached at 3.55 and 14.35 MPa, respectively, reduced by 31.5 and 48.9% correspondingly in contrast with specimens without rubber particles, and the decline rate of strength performance was more obvious. In terms of technical and economical performance comprehensively, 20 and 30 vol %

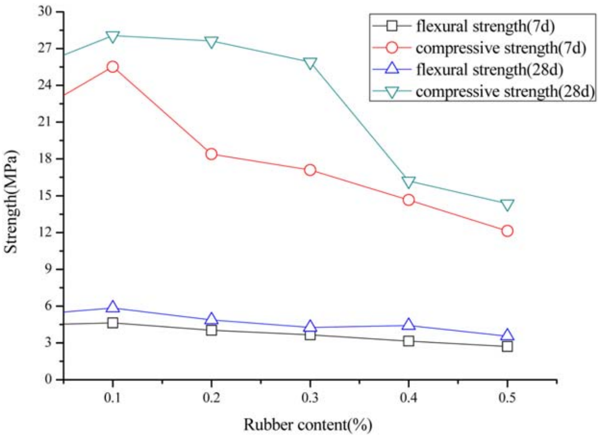


Figure 1. The influence of rubber content on the strength properties of ordinary mortar. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

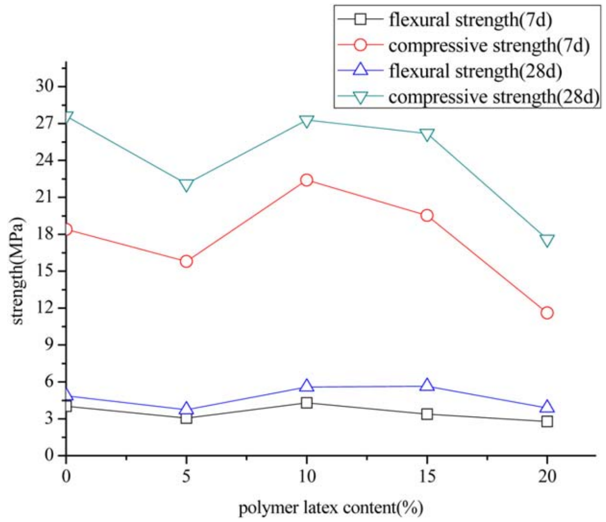


Figure 2. The strength properties of modified mortar at 20 vol % of rubber particles. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

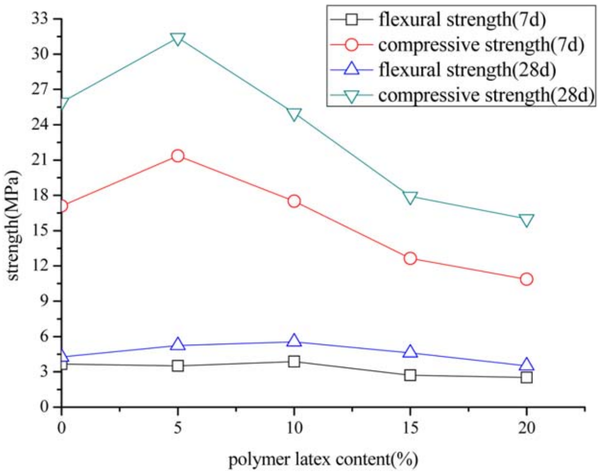


Figure 3. The strength properties of modified mortar at 30 vol % of rubber particles. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

of rubber particles were preferable and further study would be performed based on these additions.

Influence of PP Fiber and SBR Latex on the Strength Properties of Rubber Mortar

The effects of PP fiber and SBR latex on the strength properties of rubber mortar are revealed in Figures 2 and 3. In each specimen, the content of PP fiber was fixed to 0.1 vol %. Regarding test groups included with 20 vol % of rubber particles (as given in Figure 2), the polymer–cement ratio of SBR latex was chosen at 5, 10, 15, and 20% separately. Mixed with 5% polymer–cement ratio of SBR latex, the compressive and flexural strength of rubber mortar declined to a certain degree, and cured for 28 days, the flexural and compressive strength of mortar were 3.74 and 22.1 MPa, and the decline rates were 23.2 and 23.1%, respectively. As the content of SBR latex rose, the flexural strength of rubber mortar grew from a certain degree, whereas the compressive strength diminished. The compressive and flexural strength of specimens reached optimum at 10% polymer–cement ratio of SBR latex.

With respect to test groups with 30 vol % of rubber particles (as given in Figure 3), as the content of SBR latex rose, the compressive strength of rubber mortar grew initially to some degree; the compressive strength of rubber mortar cured in 28 days was the maximum at 5% polymer–cement ratio of SBR latex, and the increase rate was 21.2% in comparison with the specimens without SBR latex. With the content of SBR latex increasing further, its compressive strength confronted a drastic reduction. Although the content of SBR latex grew, the flexural strength of rubber mortar decreased after the initial increase similarly. In an curing age of 28 days, the flexural strength of rubber mortar was the greatest at 10% polymer–cement ratio of SBR latex, attaining at 5.55 MPa, an increase of 30.3% compared with the control specimens. When the polymer–cement ratio of SBR latex was greater than 10%, the flexural strength of rubber mortar fell, but the reduction rate was not apparent as its compressive strength.

Therefore, the flexural strength of specimens rose to some degree after it was modified by PP fiber and SBR latex. Meanwhile, the compressive strength of specimens faced a significant reduction, indicating a manifest improvement on the ratio of flexural strength to compressive strength. The result of the ratio of flexural strength to compressive strength was shown in Table III. This ratio could indicate the flexibility of the rubber mortar to some degree. With the addition of SBR latex increased, the ratio increased by 5–25%, and it showed that the flexibility of the rubber mortar reinforced.

Table III. Influence of Modifiers on the Ratio of Flexural Strength to Compressive Strength

	No rubber particle		With 30 vol % of rubber particles		With 20 vol % of rubber particles	
P/C (%)	7 d	28 d	7 d	28 d	7 d	28 d
0	0.1951	0.1836	0.2140	0.1645	0.2185	0.1763
5	0.1874	0.1732	0.1644	0.1669	0.1937	0.1692
10	0.2025	0.2153	0.2211	0.2220	0.1915	0.2048
15	0.2157	0.2372	0.2142	0.2570	0.1726	0.2157
20	0.2328	0.2213	0.2318	0.2194	0.2397	0.2205

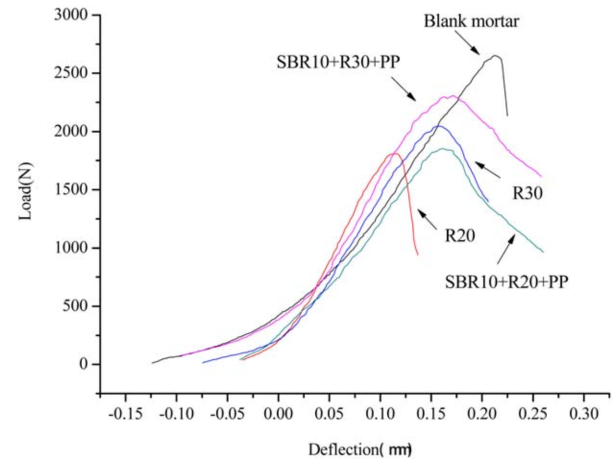


Figure 4. The relationship of load–deflection curves for the selected specimens. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Influence of PP Fiber and SBR Latex on the Flexural Toughness of Rubber Mortar

Toughness is a type of capacity of absorbing energy subjected to the impact of external load.[24–26] The load–deflection curve of specimens was demonstrated in Figure 4. The sample of control mortar had no rubber particle and modifiers. The samples of R20 and R30 indicated that the ones only added 20 and 30 vol %, respectively. The sample of SBR10+R20+PP indicated that the one added 10% polymer–cement ratio of SBR latex, 20 vol % of rubber particles, and 0.1 vol % PP fiber. The sample of SBR10+R30+PP indicated 10% polymer–cement ratio of SBR latex, 20 vol % of rubber particles, and 0.1 vol % PP fibers were added into the cement mortar.

It was observed from the load–deflection curve of different specimens that the ultimate bending strength of control specimens was the greatest, but the specimens appeared brittle failure soon after reaching at the ultimate bending strength; with the inclusion of 20 or 30 vol % of rubber particles, specimens presented apparent strain yield stage to a certain extent after arriving at ultimate strength, revealing that the flexibility of the specimens boosted to some extent. In comparison, the flexibility of rubber mortar with the addition of 30 vol % of rubber particles was superior to the counterpart of 20 vol % of rubber particles of specimens; the strain yield stage of specimens appeared more manifest at 10% polymer–cement ratio of SBR latex and 0.1 vol % of PP fiber, thus the flexural toughness of specimens improved substantially.

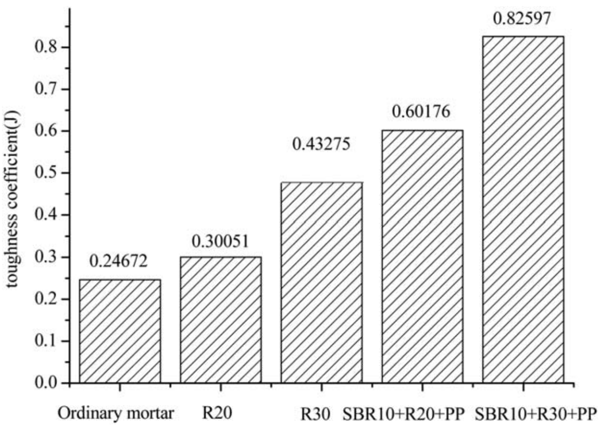


Figure 5. The toughness index for the selected specimens.

The toughness index calculated was presented in Figure 5 according to the methods proposed by the Japan JSCE-SF4. In this experiment, the flexural toughness index represented the toughening effect, and the test results showed that after the control specimens included with rubber particles, the flexural toughness index of specimens promoted from a certain degree. The flexural toughness index of R20 specimens rose, and the increase rate was 21.8%, as well as the counterpart of R30 specimens grew by 75.4% compared with control specimens. The toughening effect of PP fiber and SBR latex on rubber mortar was particularly evident. The flexural toughness index of SBR10+R20+PP specimens rose by 100.2%, compared to that of R20 specimens; meanwhile, in comparison with the flexural toughness index of R30 specimens, the increase rate for that of SBR10+R30+PP specimens was 90.9%.

Influence of PP Fiber and SBR Latex on the Flexural Elastic Modulus of Rubber Mortar

According to the preliminary experiments, some preferred experiment groups were selected and displayed in the table below. Through the universal servo instrument (MTS), the flexural elastic modulus of specimens was tested and the results were given in Figure 6. In these tests, the addition of PP fiber was fixed to 0.1 vol % of the mortar.

It could be observed from Figure 6 that after the addition of PP fiber and SBR latex, compared with the control rubber mortar sample without modifiers, the elastic modulus of modified mortar confronted a reduction to a certain degree, which revealed that the modifiers exerted flexible effects on mortar. The elastic modulus of mortar was the minimum when the modifier groups was SBR10+R30+PP, arriving at 803.83 MPa, an decrease of 61.6% than the control mortar without rubber and modifiers, and it is an indication of excellent flexibility of

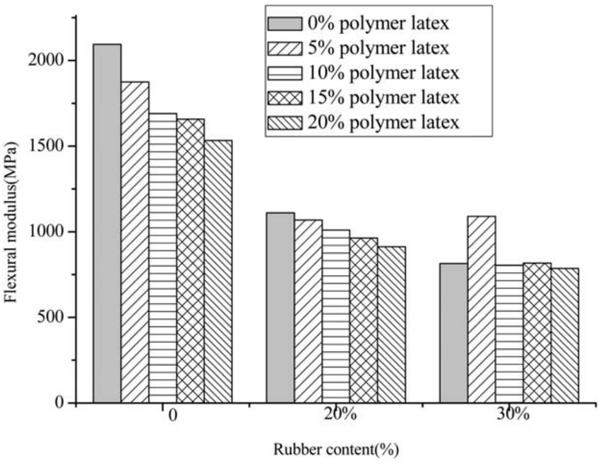
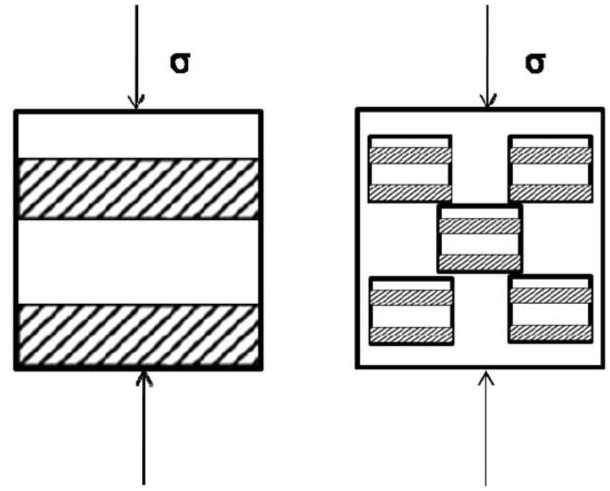


Figure 6. The elastic modulus of composite-modified cement mortar (MPa).



(a) series structure model (b) dispersion structure model

Figure 7. The schematic diagram of the constitutive model of FPMRM.

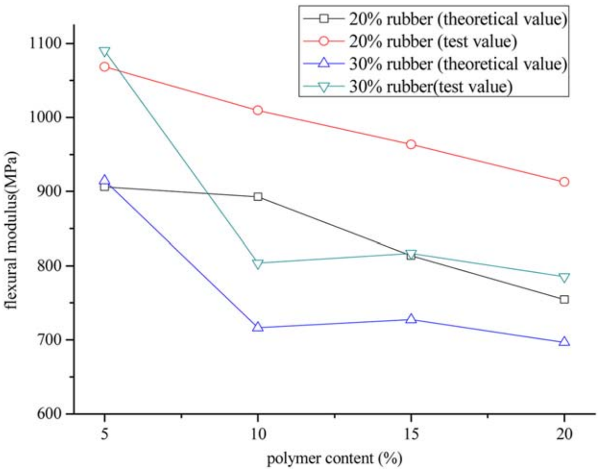


Figure 8. The comparison of elastic modulus between calculated and tested values. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

mortar. With the addition of PP fiber and SBR latex into the rubber mortar, the flexural elastic modulus could reduce by 4–27%. The unilateral content increase of rubber particles or SBR latex would both reduce the elastic modulus of specimens to some extent, thus enhancing the flexibility.

The mechanism of the flexible effect on mortar may be in that when the polymer particles coagulate, which gives rise to the formation of high intensity and strong cohesive films, which in turn boosted the flexibility of mortar. And the flexible reason of PP fiber and rubber particles may due to its low elastic modulus, leading to the decline of overall elastic modulus of mortar matrix so that the flexibility of mortar improves.

Constitutive Relation of PP Fiber and SBR Latex Compound-Modified Rubber Mortar

The function of material properties was based on the elastic modulus to a certain extent, which could provide a tool for the better understanding of the materials in response to stress.[27,28] Cement mortar is a kind of polyphase and compound material with granular type, whereas polymer-modified rubber mortar is undoubtedly a new kind of composite material with a combination of rigid body and elastomer. A great number of new interface forms within the materials, besides, internal micro structure of materials will change as well. To better simulate the mechanical performance of polymer-modified rubber mortar system, rational structural model needs to build.

At this point, the new type of rubber mortar was regarded as a three-phase composite material composed of the polymer-modified cement stone (a composition of PP fiber, polymer, and cement paste), river sands, and rubber particles. The dispersion model was composed of PP fiber, polymer, and cement stone [as given in Figure 7(b)]. The content of PP fiber was little in the rubber mortar; so, we ignored the PP fiber in the constitutive model.

First, polymer, as a dispersed phase, distributes randomly in the continuous matrix composed of cement stone. The elastic modulus of polymer-modified cement stone can be obtained as follows through the dispersion model as in formula (2):

$$E_{\mathrm{pm}}=E_m\frac{1+2V_p\left(\frac{\alpha-1}{\alpha+2}\right)}{1-V_p\left(\frac{\alpha-1}{\alpha+2}\right)}\qquad \alpha=\frac{E_p}{E_m} \tag{2}$$

where E_{pm} is the elastic modulus of polymer modified cement stone, E_m is the elastic modulus of cement stone without polymer, E_p and V_p are the elastic modulus and volume fraction of polymer, respectively.

Second, sand and rubber particles, as dispersed phases, randomly dispersed in a continuous matrix composed of cement stone. In cement matrix, the stress that the sand and rubber particles exerts is considered equal, which follows the series model between them [as shown in Figure 7(a)]. Then, on the basis of the series model between sands and rubber particles, the equivalent elastic modulus, E_{ar}, of sand and rubber particles can be attained as follows:

$$\frac{1}{E_{\mathrm{ar}}}=\frac{V_r}{E_r}+\frac{V_a}{E_a}\Rightarrow E_{\mathrm{ar}}=\frac{E_rE_a}{E_rV_a+E_aV_r} \tag{3}$$

where E_{ar} is the composite elastic modulus of sand and rubber particles in series, E_m is the elastic modulus of rubber, and V_r and V_a are the volume fraction of rubber particles and sand, respectively.

Eventually, sand and rubber particles were randomly distributed in polymer-modified cement continuous matrix; therefore, sand, rubber particles, and cement matrix followed the dispersion model as well. Through the computation formula of three-phase composite dispersion model, the computation formula of elastic modulus of new type of fiber and polymer-modified rubber mortar was:

$$E_0=E_{\mathrm{pm}}\frac{1+2V_{\mathrm{ar}}\left(\frac{\alpha-1}{\alpha+2}\right)}{1-V_{\mathrm{ar}}\left(\frac{\alpha-1}{\alpha+2}\right)}\qquad \alpha=\frac{E_{\mathrm{ar}}}{E_{\mathrm{pm}}} \tag{4}$$

where E_0 is the elastic modulus of fiber and polymer-modified cement rubber mortar and V_{ar} is the total volume fraction of sands and rubber particles.

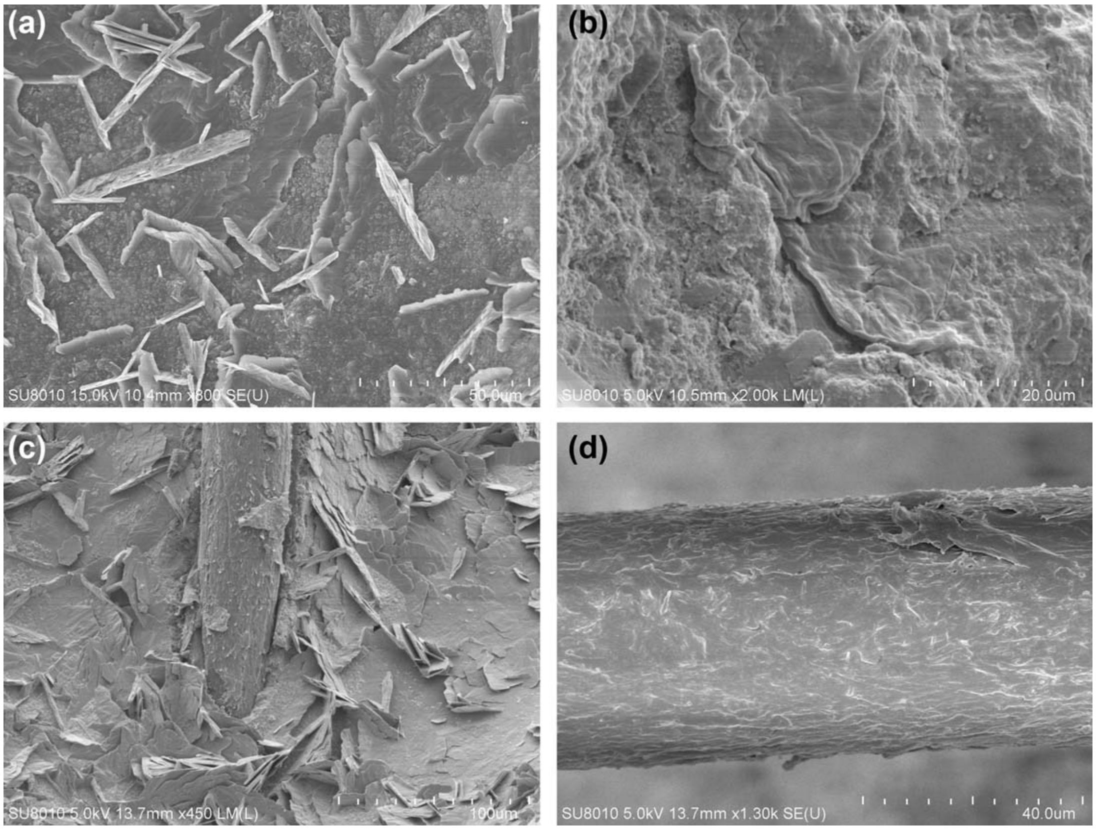


Figure 9. The microstructure of PP fiber and polymer film in FPMRM: (a) The C—S—H gel and AFt in FPMRM, (b) The polymer film in FPMRM, (c) The PP fiber in FPMRM, and (d) The polymer film on PP fiber.

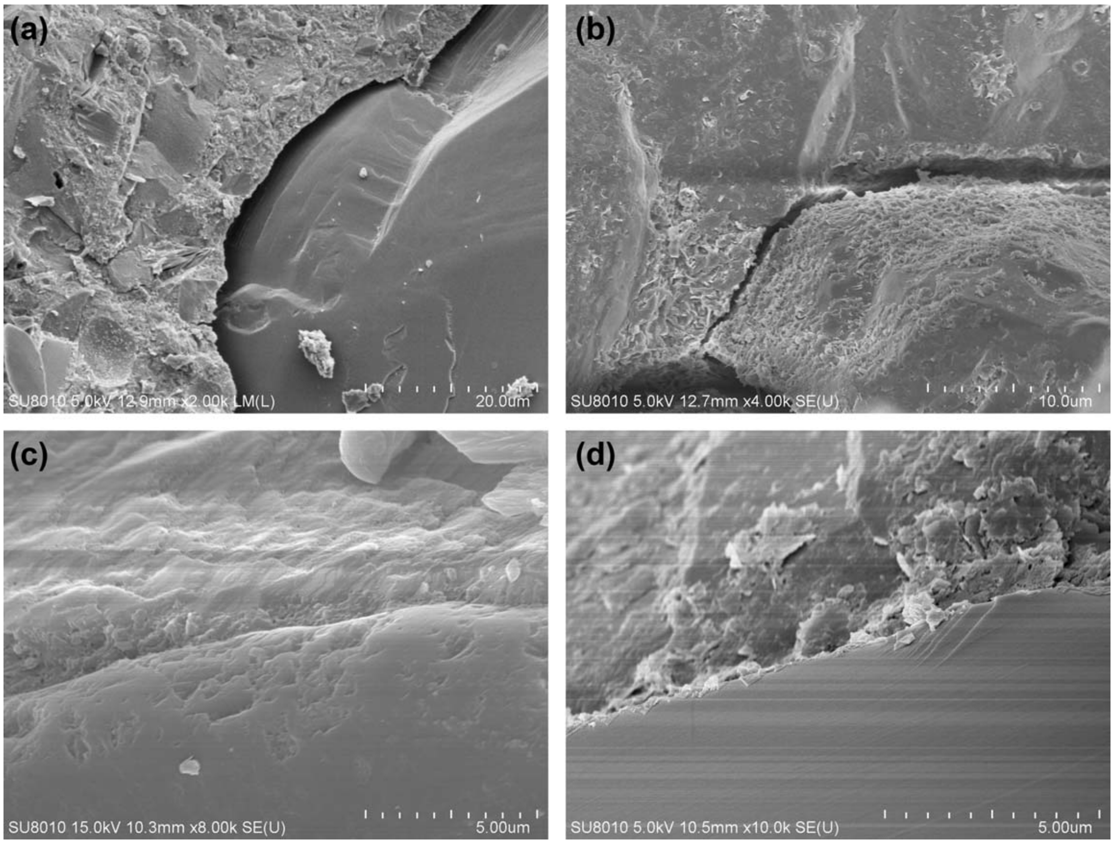


Figure 10. The microstructures of the selected mortar samples: (a) The interfacial transition zone between aggregate and cement paste in control sample (b) The interfacial transition zone between aggregate and rubber particle in control sample, (c) The interfacial transition zone between the aggregate and cement paste in FPMRM, and (d) The interfacial transition zone between the aggregate and rubber particle in FPMRM.

The comparison of elastic modulus between the calculated value and the test value is shown in Figure 8. The theoretical value of this rubber mortar was calculated using formula (4). We could conclude from the figure that the elasticity modulus of the theoretical value was close to the test value. It illustrated that the three-phase composite dispersion model was relatively reliable to simulate the mechanics behavior of elastic rubber particles in rigid cement mortar matrix. It could also contribute to analysis the mechanism of interaction between the rubber particles and other components in the cement mortar.

Microstructure of PP Fiber and SBR Latex Compound-Modified Rubber Mortar

The microstructure of different specimens of rubber mortar was observed by SEM. Figure 9(a) illustrated the morphology of the cement paste in the material, some C—S—H gel and fine needle-like AFt could be found. The foil-like C—S—H gel was the main hydration product of cement, and it contributed to the major strength development in mortar. The fine needle-like AFt crosslinking in the foil-like C—S—H gel leaded to the strength improvement. Figure 9(b) demonstrated that the film formed by SBR polymer is due to the dehydration of latex, which resulted in the ductility improvement of the rubber mortar. The crosslinking films of polymer in the cement product enhanced the flexibility and ductility of rubber mortar. It could be seen from Figure 9(c,d) that when PP fiber was pulled out from the cement mortar matrix, the surface of the fiber was full with large amount of hydration and the film-like products. With the hydration of cement carrying on and the dehydration of polymer to form the film gradually, at the interface between cement mortar matrix and PP fiber, there is a transitional layer of thin polymer films, which makes the interfaces between the cement hydrates and aggregates and among the organic fibers bond cohesively, thereby PP fiber could more effectively come into full play in the matrix. Figure 10(a,b) reveals the microstructure of interfacial transition zone (ITZ) between the cement paste and aggregates/rubber particles in the control sample without two modifiers. It could be seen that the defects of ITZ between the cement paste and aggregates/rubber particles are apparent. In addition, there are manifest cracks in the ITZ, and the cracks were long and widespread. In comparison, Figure 10(c,d) showed the dense ITZ of specimens with the addition of polymer and the PP fiber, and in the ITZ, there are barely apparent defects, indicating that the inclusion of polymer latex could effectively fill the internal macro and micro defects of cement matrix, thus improving the degree of density into the ITZ.

CONCLUSIONS

Based on the experimental results and microstructure observation, the following conclusions can be drawn:

1. Compared to the rubber mortar samples without modifiers, with the addition of SBR latex and PP fiber into the rubber mortar, the flexural strength appeared a certain degree of increase by 5–30%, the compressive strength of specimens faced a significant reduction by 10–23%. It indicated a manifest improvement on the ratio of flexural-compressive strength and the flexibility of the rubber mortar reinforced.
2. The addition of PP fiber and SBR polymer latex to rubber mortar was seen to enhance the flexural toughness index by about 50–100%. One of the major contributions of these two types of modified materials is related with damage energy absorption. It enables the rubber mortar to withstand a certain amount of load after the appearance of cracks in mortar subjected to bending load.
3. The flexural elastic modulus of mortar significantly reduced when sands were replaced by crumb rubber particles. As the addition of PP fiber and SBR latex, the flexural elastic modulus of rubber mortar could further reduce by 4–27%, which indicated excellent flexibility.
4. The new type of rubber mortar was regarded as a three-phase composite material composed of sand, rubber particles, and polymer-modified cement stone. On the basis of the series model and dispersion model of the three-phase composite materials, the three-phase composite dispersion model of the FPMRM was put forward. On the basis of the calculated value and the test value of elastic modulus, the three-phase composite dispersion model was relatively reliable.
5. At the interface between cement hydration and PP fiber, there is a transitional layer of thin polymer films, which makes the interface bond more cohesively. The inclusion of polymer latex could effectively fill the internal macro and micro defects of cement matrix, thus improving the degree of density of ITZ. The reinforcement of interfacial cohesive state among rubber particles, aggregates, and the cement hydration could lead to improve the mechanical properties of the rubber mortar.

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