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Effect of Different Fibers on Shrinkage Properties and Bonding Properties of Geopolymer Mortar Repair Materials and Analysis of the Mechanism

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Abstract: The geopolymer uses fly ash, slag, and other solid wastes as raw materials and is widely used in building repair, but it is brittle and can be made tougher by incorporating fibers. In this study, polyvinyl alcohol (PVA) fibers, polyoxymethylene (POM) fibers, and polypropylene (PP) fibers were incorporated into the geopolymer mortar repair material, and the geopolymer was tested by changing the amount of fibers incorporation as well as the type. The effect of different fibers on the geopolymer mortar repair material was analyzed by comparing the flexural strength, compressive strength, flexural toughness, shrinkage, and bonding properties with cement mortar of different samples. The geopolymer was analyzed by Diffraction of X-rays (XDR) and Scanning Electron Microscopy (SEM) to further understand the hydration products and microstructure of the geopolymer. The results showed that the incorporation of fibers reduced the flexural strength and increased the compressive strength of the geopolymer mortar repair material; the mechanical properties of the geopolymer mortar repair material decreased with the increase in fiber incorporation, and the best mechanical properties of the geopolymer mortar repair material incorporated with 1.0% PP fibers; the toughening effect of PVA fiber was best when the amount of fiber incorporated was the same; the shrinkage properties of the geopolymer were good and had little effects on the building repair; the bonding properties of repaired specimens repaired with geopolymer mortar repair materials depended on the bonding area of the fracture surface, and the bonding area was enhanced with the increase in fiber incorporation; the XRD pattern showed that the hydration products of the geopolymer were mainly $CaCO_3$ and C–S–H gels.

Keywords: geopolymer mortar repair material; fiber; flexural toughness; shrinkage property; bonding property; micro characterization

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1. Introduction

In recent years, the use of cement has been restricted due to its high impact on the environment [1]. Geopolymer, as an alternative to cement, can use fly ash, slag, silica fume, and other solid wastes as raw materials [2]. It has good mechanical properties, acid and alkali corrosion resistance, high fire resistance, frost and seepage resistance, fast setting, and early strength. Thus, it can be used as an alternative to cement and have good application prospects [3]. Although geopolymer has many advantages, microcracks are also prevalent in geopolymer materials [4], and the extension of microcracks leads to brittle damage of the geopolymer matrix, so the problem of the brittleness of geopolymer needs to be resolved urgently.

Fibers with large elastic modulus, low plastic deformation, and high strength [5] are now widely used to enhance the properties of geopolymer [6]. The debonding, sliding, and pulling out of fibers consume a lot of energy that would have extended cracks [3], so incorporating fibers into the geopolymer matrix can be a good way to increase the toughness of the geopolymer [7]. However, the fiber incorporation cannot be too high or too low. When the fiber incorporation is lower than the lower threshold, the toughness effect of the fiber on the geopolymer cannot be effectively reflected. When the fiber is higher than the higher threshold, the dispersion of fiber will become very poor, easy to agglomerate but not conducive to the enhancement of geopolymer performance. In this study, PVA fibers, POM fibers, and PP fibers were used to improve the toughness of the geopolymer and increase the application range of the geopolymer.

In recent years, the application of fibers in geopolymers has become more and more widespread, and many scholars have conducted in-depth studies on fibers. The incorporation of fibers has different effects on the flowability [8,9], density [10,11], shrinkage [12,13], and mechanical properties [14–21] of the geopolymer. Xu et al. [14] studied the effect of two different lengths of PVA fibers on the geopolymer, and the results showed that 12 mm PVA fibers toughened the geopolymer better than 8 mm PVA fibers. Li et al. [16] studied the effect of low-strength polyvinyl alcohol (L-PVA) fibers, high-strength polyvinyl alcohol (H-PVA) fibers, and polyethylene (PE) fibers on geopolymer by changing the fiber type and fiber incorporation amount, and obtained the optimal incorporation amounts of 1.75%, 2.25% and 1.5% for the three; however, PE fiber was not widely used due to its high price. Khan et al. [22] investigated the effect of polyethylene terephthalate (PET) fibers, PVA fibers, and PP fibers on the mechanical properties of engineered cementitious and geopolymer composites (ECC and EGC) blends, respectively. It was found that fiber incorporation increased the compressive strength and elastic modulus of ECC and EGC, with PVA fibers performing significantly better than PET and PP fibers. Cai et al. [23] varied the form of PVA fiber incorporation and the amount of incorporation to investigate the properties of the geopolymer. The results showed that the incorporation of PVA powder did not enhance the mechanical properties of the geopolymer, and no reaction occurred. Deng et al. [24] blended PVA fibers into the geopolymer to reduce its dry shrinkage and brittleness, and the results showed that the 20d shrinkage of PVA-EGC with fiber incorporation of 0.3% and 0.6% was 53.45% and 69.7% lower than that of the geopolymer matrix, respectively, and the larger the PVA fiber incorporation, the more obvious the effect of reducing the shrinkage.

The ability of a geopolymer to perform well as a building repair material depends on the strength of the bond between the geopolymer and the surrounding building. Ling et al. [25] concluded by analyzing the relationship between bond stress and slip that incorporating fibers could enhance the bond strength between EGC and reinforcing steel. Zhang et al. [26] found via their study that the bond strength of geopolymers located above 300 °C decreased with increasing temperature, and it decreased at the same rate as the splitting tensile strength. Zanotti et al. [27] investigated the bond strength between geopolymer mortar repair materials and concrete by incorporating PVA fibers and changing the curing programs. The results showed that the incorporation of 0.5% PVA fibers increased the cohesion by 65% for thermally cured specimens and by 204% for environmentally cured specimens. Kumar et al. [28] investigated the bond strength of geopolymer mortar repair materials by varying the sand binder (S/B) ratio and showed that the interfacial bond strength between geopolymer mortar repair materials and concrete increased with the increase in the S/B ratio. There are many more articles exploring geopolymer mortar repair mortar [29–35], and the current research on geopolymer repair materials mainly focuses on changing the geopolymer matrix. A few scholars have studied the effect of PVA fibers, but the application of POM fibers and PP fibers in the field of geopolymer mortar repair materials is relatively small, and further research is needed.

In this study, PVA fibers, POM fibers, and PP fibers were incorporated into the geopolymer, and the flexural strength, compressive strength, flexural toughness, shrinkage properties, bonding properties, and microstructure were measured, and each index was analyzed comprehensively to investigate the effects of different fibers on the shrinkage and bonding properties of the geopolymer mortar repair material.

2. Experimental Test

2.1. Materials

The materials for this experiment included Class II fly ash, Class S95 slag, alkali activator, quartz sand, and three different types of fibers. Fly ash had a specific surface area of 400 m^2/kg and a density of 2.24 g/cm^3, and slag had a specific surface area of 440 m^2/kg and a density of 2.88 g/cm^3. The alkali activator with a modulus of 1.5 was prepared by mixing sodium hydroxide and water glass. Quartz sand used 40–80 mesh. The fibers used were PVA fiber, PP fiber, and POM fiber, all with a length of 12mm.

The specific chemical composition of the raw materials is shown in Table 1. The specific properties of the fibers are shown in Table 2.

Table 1. Chemical composition of fly ash and slag (wt.%).

Material	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	MnO	TiO_2	Na_2O	K_2O	P_2O_5	LOI
Fly ash	51.99	5.55	37.08	4.10	1.37	0.05	1.36	1.48	0.95	0.06	1.95
Slag	35.01	27.56	21.09	0.32	12.87	0.16	0.26	0.36	0.27	0.05	1.49

Table 2. Basic properties of fibers.

Type	Tensile Strength (MPa)	Modulus of Elasticity (GPa)	Dry Elongation at Break (%)	Linear Density (g/cm^3)	Diameter (μm)
PVA fiber	1600	35	17 ± 3.0	1.3	40
POM fiber	800	10	30	1.4	200
PP fiber	450	8	21	0.91	200

2.2. Experimental Program

The ratio of fly ash and slag in the geopolymer was changed and divided into six groups from G1 to G6. When making the specimens, 1.0% of PVA, POM, and PP fibers were incorporated, respectively, into the six groups of geopolymers, and then the fluidity, flexural strength, and compressive strength of the specimens were tested. Comprehensive analysis of the experimental data found that the properties of G5 incorporated with fibers were the best, at which time the ratio of fly ash to slag was 3:7.

The geopolymer matrix was obtained by mixing fly ash, slag, quartz sand, water, and alkali activator. Fibers were incorporated into the geopolymer matrix, the amount and type of fibers were varied, and the mechanical properties and toughness were analyzed. It was concluded that the properties of the fiber-reinforced geopolymer mortar repair material were better when the fiber incorporation was 1%. Xu et al. [14] concluded that the specimens incorporated with 2.0% PVA fibers had the best toughness. On this basis, we designed experiments to test the shrinkage and bonding properties of geopolymer mortar repair materials.

The results of the experiments exploring the best ratio of fly ash to slag are shown in Table 3, the best ratio of geopolymer matrix is shown in Table 4, and the experimental program is shown in Table 5.

Table 3. Results of the experiments exploring the best ratio of fly ash to slag.

Specimen	Fiber	Water (g)	Slag (g)	Fly Ash (g)	Alkali Activator (g)	Fluidity (mm)	Compressive Strength (MPa)	Flexural Strength (MPa)
G1-PVA	1.0% PVA	327.8	0	1215.2	257	60	31.8	5.0
G2-PVA	1.0% PVA	327.8	364.6	850.6	257	60	42.2	8.6
G3-PVA	1.0% PVA	327.8	486.1	729.1	257	60	44.0	8.9
G4-PVA	1.0% PVA	327.8	729.1	486.1	257	100	58.8	9.8
G5-PVA	1.0% PVA	327.8	850.6	364.6	257	115	63.1	10.2

Table 3. *Cont.*

Specimen	Fiber	Water (g)	Slag (g)	Fly Ash (g)	Alkali Activator (g)	Fluidity (mm)	Compressive Strength (MPa)	Flexural Strength (MPa)
G6-PVA	1.0% PVA	327.8	1215.2	0	257	140	70.2	10.4
G1-POM	1.0% POM	327.8	0	1215.2	257	170	37.8	5.8
G2-POM	1.0% POM	327.8	364.6	850.6	257	175	48.5	8.5
G3-POM	1.0% POM	327.8	486.1	729.1	257	171	48.6	8.5
G4-POM	1.0% POM	327.8	729.1	486.1	257	173	61.2	10.4
G5-POM	1.0% POM	327.8	850.6	364.6	257	176	65.4	11.5
G6-POM	1.0% POM	327.8	1215.2	0	257	178	72.8	9.3
G1-PP	1.0% PP	327.8	0	1215.2	257	135	40.5	7.2
G2-PP	1.0% PP	327.8	364.6	850.6	257	142	49.8	9.7
G3-PP	1.0% PP	327.8	486.1	729.1	257	175	56.8	10.0
G4-PP	1.0% PP	327.8	729.1	486.1	257	185	62.9	11.2
G5-PP	1.0% PP	327.8	850.6	364.6	257	185	69.2	11.4
G6-PP	1.0% PP	327.8	1215.2	0	257	180	75.0	11.2

Table 4. Best ratio of geopolymer matrix (g).

Fly Ash	Slag	Quartz Sand	Water	Alkali Activator
241.8	564.2	806	217.43	170.47

Table 5. Experimental program.

Specimen	Volume Fraction (%)	PVA Fiber (g)	POM Fiber (g)	PP Fiber (g)
A0	0	0	0	0
A1	1	7.3	0	0
A2	1	0	7.96	0
A3	1	0	0	5.04
A4	2	14.6	0	0
A5	2	0	15.92	0
A6	2	0	0	10.08

2.3. Test Methods

2.3.1. Mechanical Properties

When making the specimen, first pour the solid material (fly ash, slag, and quartz sand) into the mixer and stir well. While the mixer was rotating, a small amount of fiber was added several times, and the alkali activator and water after the fiber and solid material were fully mixed. After mixing in the mixer for 4 min, the slurry was immediately poured into a 40 mm × 40 mm × 160 mm triplex mold and fully vibrated. After the specimen was smoothed and formed, the surface was immediately covered with plastic film and put into a standard curing box with a temperature of 20 °C ± 2 °C and relative humidity of 95% or more and maintained until the specified age. The flexural and compressive strengths of the specimens were tested according to the National Standard GB/T 17671-20219 of the People's Republic of China. When measuring the flexural strength of a specimen, the specimen is placed on the supporting column of the testing machine, with the long axis of the specimen perpendicular to the supporting column, and the load is applied vertically via the loading column uniformly at the midpoint of the specimen until it breaks. After completing the flexural test, the two fractured halves of the specimen are removed and used for the compressive test. When measuring the compressive strength, the load is applied uniformly using the press plate to half of the specimen until it breaks. When measuring compressive strength, a load is applied uniformly to a halved specimen using a press plate until the specimen breaks.

2.3.2. Flexural Toughness

In this test, a four-point bending experiment was used to measure the flexural toughness of fiber-reinforced geopolymer mortar repair materials. The size of the specimen was 400 mm × 100 mm × 15 mm, and the procedure for making the specimen was unchanged.

The experiment was carried out on a hydraulic servo experimental machine and loaded according to the controlled displacement method. In order to improve the accuracy of the deflection test, the displacement of the loading point, the settlement of the specimen at the support, and the elastic deformation of the steel plate are not included in the recording process. The corresponding data were collected using computer, and the load-deflection curves were plotted for each fiber incorporation. The four-point bending experiment loading device is shown in Figure 1.

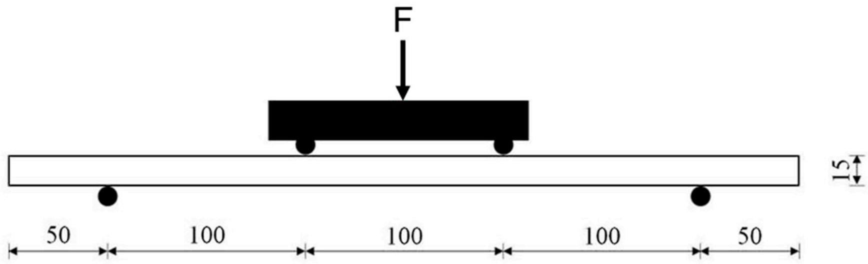


Figure 1. Schematic diagram of the four-point bending experiment loading device. (Unit: mm).

The toughness index was measured according to ASTM C1018. The toughness index is calculated according to Equation (1):

$$I_5 = \frac{T_3}{T_1},\ I_{10} = \frac{T_{5.5}}{T_1},\ I_{20} = \frac{T_{10.5}}{T_1} \tag{1}$$

where I_5, I_{10}, and I_{20} are toughness index, T_1 (T_3, $T_{5.5}$, $T_{10.5}$) is the area under the load-deflection curve at 1 (3, 5.5, 10.5) times of deflection corresponding to the point of first crack.

2.3.3. Shrinkage

Specimens were made according to the DL/T5126-2001 standard proposed by the China Institute of Water Resources and Hydropower Research.

The shrinkage rate is calculated according to Equation (2):

$$\varepsilon_t = \frac{L_t - L_0}{L_0 - 2\Delta} \times 100\%, \tag{2}$$

where ε_t is shrinkage rate in t days (%), L_0 is reference length of specimen (mm), L_t is the length of the specimen in t days (mm), and Δ is the length of the copper nail (mm).

2.3.4. Bonding Properties

Cement mortar specimens of 40 mm × 40 mm × 160 mm were prepared in advance [with a ratio of m (cement):m (quartz sand):m (water) = 1:1.8:0.38]. After 28 days of curing (the flexural strength of the specimen was 9.7 MPa, and the compressive strength was 53.5 MPa), the middle part of the cement mortar specimen was excised with a cutting machine, and the length of the excised part was controlled at about 2 cm. After putting the remaining cement mortar specimens into the two ends of the triplex mold and filling the vacant part in the middle with the geopolymer mortar repair material, pounding and smoothing with a scraper, the repaired specimens obtained were named from B0 to B6, respectively. The repaired specimens were put into the standard curing box for 28 days to test the flexural strength, and the bonding properties were expressed in flexural strength. The flexural strength of the repaired specimen was measured according to the National Standard GB/T 17671-20219 of the People's Republic of China.

The repaired specimen is shown in Figure 2.

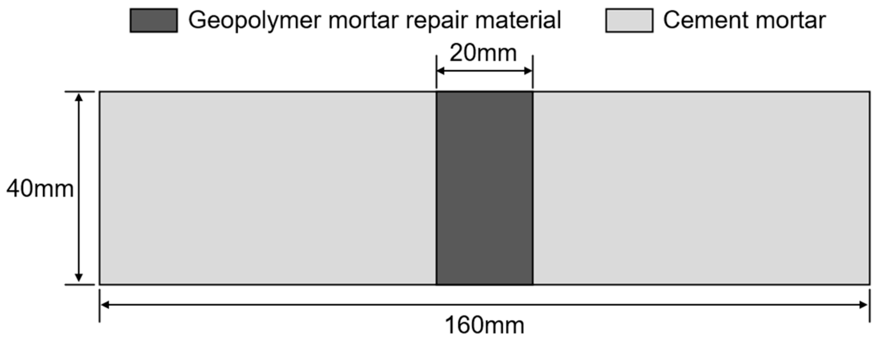


Figure 2. Schematic diagram of the repaired specimen.

2.3.5. Micro Characterization

The cured 28-day geopolymer matrix was ground into powders suitable for diffraction experiments and then prepared into a sample with a flat surface. After starting the XRD instrument and adjusting it appropriately, the sample was placed on the sample stage and clamped with clamps to ensure its stability. Via rotating the sample stage and moving the detector, the diffraction pattern of the sample was recorded, and finally, the diffraction pattern was analyzed using jade to obtain the hydration products of the geopolymer. The XRD instrument used in this experiment was the Rigaku SmartLab SE from Tokyo, Japan.

The surface of the fractured specimen was sprayed with gold, and the specimen was placed on the SEM sample stage, and the images were acquired using SEM electron beam scanning of the sample surface. The SEM instrument used in this experiment was the ZEISS GeminiSEM 300 from Jena, Germany.

3. Results

3.1. Flexural Strength

The incorporation of fibers into the geopolymer increased its toughness. However, with the incorporation of fibers, the mechanical properties of the geopolymer were changed. The specimens cured for 28 days were tested for flexural strength, and the flexural strength data were counted. The specific flexural strength data are shown in Table 6.

Table 6. Flexural strength of geopolymer mortar repair material.

Specimen	A0	A1	A2	A3	A4	A5	A6
Fiber incorporation amount (%)	0	1.0% PVA	1.0% POM	1.0% PP	2.0% PVA	2.0% POM	2.0% PP
Flexural strength (MPa)	11.7	10.2	11.4	11.5	9.1	9.1	9.7

As shown in Table 6, the incorporation of fibers reduces the flexural strength of the geopolymer mortar repair material compared to the geopolymer matrix. The reason may be that the fibers are tough, and the geopolymer in the cross-section of the specimen is replaced by the fibers, resulting in a reduction in the amount of geopolymer bonding at the cross-section. This leads to a reduction in the flexural strength of the specimen during the flexural test. The flexural strength of the geopolymer decreases as the fiber incorporation increases from 1.0% to 2.0% when the type of fiber incorporated is the same. The flexural strengths of A1, A2 and A3 are 12.09%, 25.27% and 18.56% higher than those of A4, A5 and A6, respectively. Compared to the incorporation of PP fibers or POM fibers, the incorporation of PVA fibers reduces the workability of the geopolymer, resulting in many pores in the specimen and a reduction in flexural strength. Compared to POM fibers, PP fibers have a stronger bond to the geopolymer and thus can carry more loads. The flexural strength of the geopolymer mortar repair material incorporated with PP fibers is the highest when the fiber incorporation is the same. Among them, the flexural strength of A3 is 12.75% and 0.088% higher than A1 and A2, respectively, and the flexural strength of A6 is 6.59% higher than A4 and A5, respectively.

3.2. Compressive Strength

The specimens cured for 28 days were tested for compressive strength in accordance with the specifications, and the compressive strength data were counted. The specific compressive strength data are shown in Table 7.

Table 7. Compressive strength of geopolymer mortar repair material.

Specimen	A0	A1	A2	A3	A4	A5	A6
Fiber incorporation amount (%)	0	1.0% PVA	1.0% POM	1.0% PP	2.0% PVA	2.0% POM	2.0% PP
Compressive strength (MPa)	60.5	63.1	65.4	69.2	67.3	73.2	79.8

As shown in Table 7, the incorporation of fibers increases the compressive strength of the geopolymer mortar repair material compared to the geopolymer matrix. Although the fibers replace some of the geopolymer and reduce the flexural strength, bonding between the fibers and the geopolymer still exists. This means that when subjected to pressure, the specimen is more able to resist the pressure without collapsing easily due to the synergistic effect between the fibers and the geopolymer. When the type of fibers incorporated is the same, the compressive strength of the geopolymer mortar repair material gradually increases as the fiber incorporation increases from 1.0% to 2.0%. The compressive strengths of A4, A5 and A6 are 6.66%, 11.93% and 15.32% higher than those of A1, A2 and A3, respectively. The compressive strength of the geopolymer mortar repair material incorporated with PP fibers is the highest when the fiber incorporation is the same. The reason for this is the same as the reason for the highest flexural strength of geopolymer mortar repair materials incorporated with PP fibers. Among them, the compressive strength of A3 is 9.67% and 5.81% higher than that of A1 and A2, respectively, and the compressive strength of A6 is 18.57% and 9.02% higher than that of A4 and A5, respectively.

3.3. Flexural Toughness

It has been known that the toughness of geopolymers is increased with the increase in fiber incorporation [14,36]. Combined with the analysis of the flexural and compressive strengths of the fiber-reinforced geopolymer, it can be seen that the mechanical properties of the geopolymer are better when the fiber incorporation is 1.0%. Therefore, 1.0% of PVA fibers, POM fibers, and PP fibers were incorporated into the geopolymer to obtain three sets of specimens, A-PVA, A-POM, and A-PP, respectively. The effects of the three fibers on the flexural toughness of the geopolymer were investigated by performing four-point bending experiments on the three sets of specimens and obtaining their respective load-deflection curves. The toughness index was measured according to ASTM C1018.

The load-deflection curves obtained from the experiments are shown in Figure 3, and the results of the flexural toughness experiments are shown in Table 8.

Figure 3a shows that the load on A-PVA gradually increases as the deflection lies in the range of 0–1.5 mm. When the deflection is in the range of 1.5–2.6 mm, the A-PVA is in the yield stage, and as the deflection increases, the load remains constant and is maintained at about 52 N. When the deflection is above 2.6 mm, there are two peaks in the curve as the deflection increases, which occur at deflections of 3.61 mm and 3.98 mm, respectively. Figure 3b,c show that the load deflection curves of A-POM and A-PP are similar in that they each have two yield stages and one peak. This indicates that the POM and PP fibers have similar patterns of influence on the toughness of the geopolymer. The peak of A-POM is 341.6 N, and the peak of A-PP is 472.3 N.

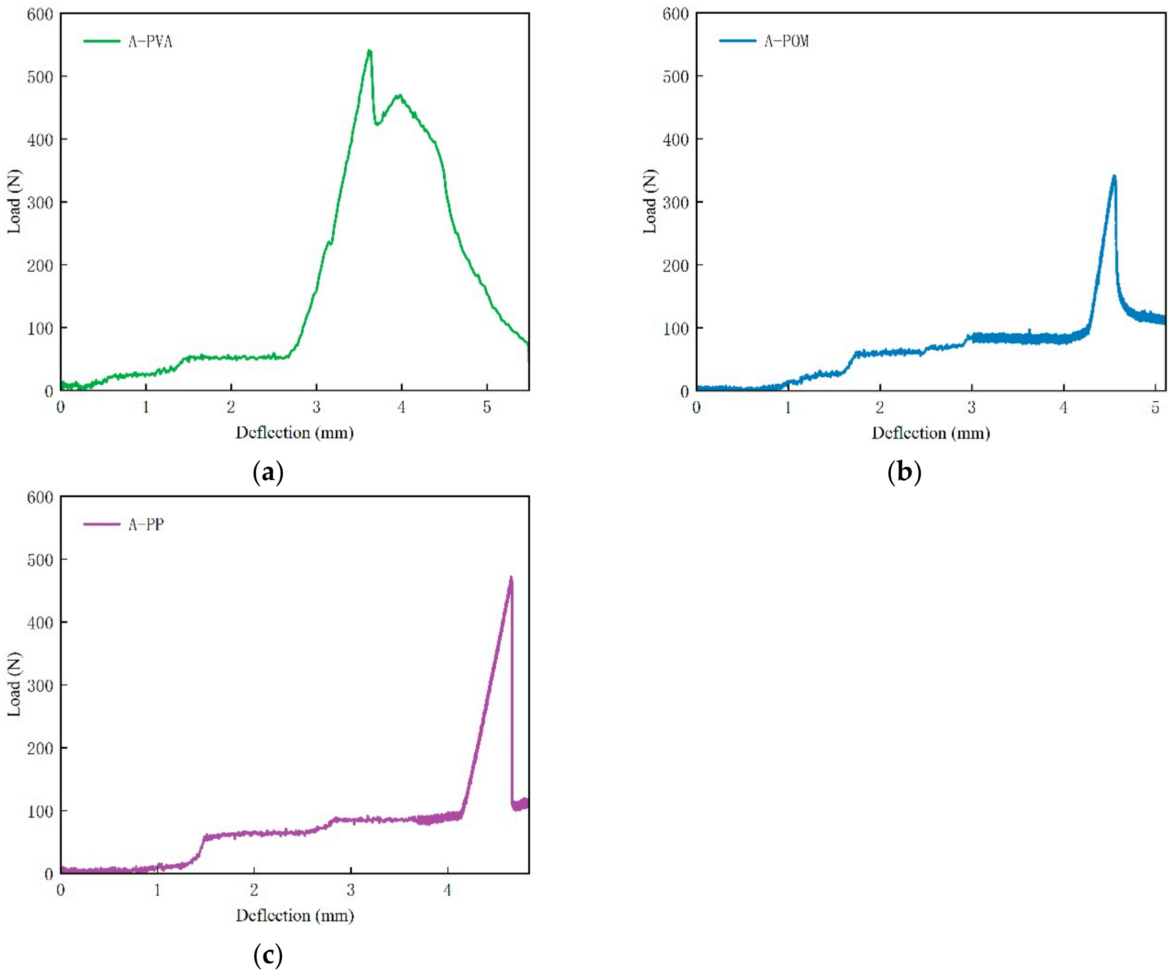


Figure 3. Load-deflection curves of geopolymer mortar repair materials: (**a**) A-PVA; (**b**) A-POM; (**c**) A-PP.

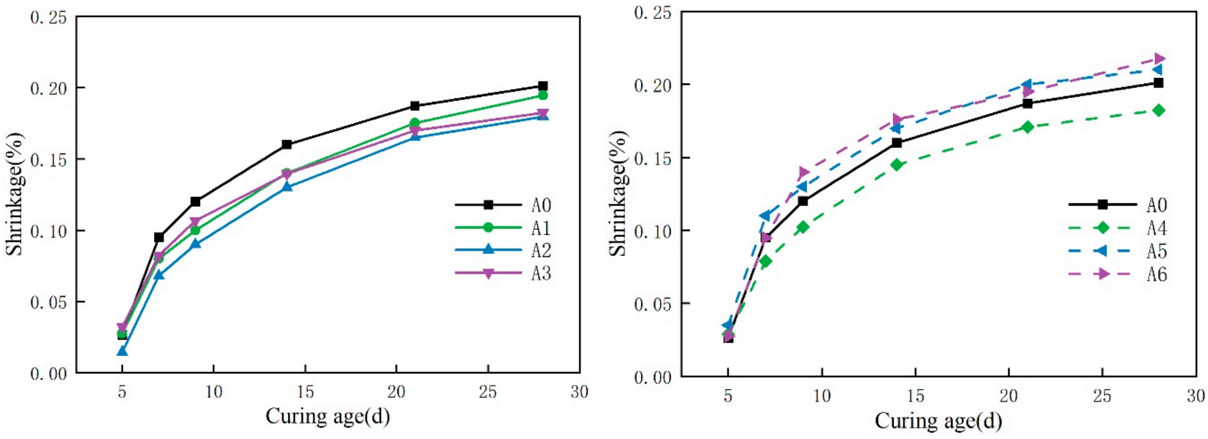
Table 8. Results of the flexural toughness experiments.

Specimen	Ultimate Flexural Load (N)	I_5	I_{10}	I_{20}
A-PVA	541.4	7.4	64.4	71.1
A-POM	341.6	18.5	21.0	21.0
A-PP	472.3	21.4	28.9	28.9

From Table 8, all the I_5, I_{10}, and I_{20} indexes are higher than 5, 10, and 20, respectively, indicating that the incorporation of all three types of fibers can avoid brittle damage to the geopolymer. This is mainly because the fiber bridging, breaking, debonding, and pulling out play an important role. Based on the toughness index, it can be concluded that A-PVA has the best toughness. This is mainly due to the different bond strengths of the different fibers at the interface with the geopolymer matrix. Compared with POM and PP fibers, the higher tensile strength and good bond strength with the geopolymer matrix make PVA fibers consume the most energy in the process of breaking, debonding, and pulling out, so the toughening effect of PVA fibers is the most obvious. As the deflection gradually exceeded the deflection corresponding to the peak, the load on A-PVA gradually decreased, while the load on both A-POM and A-PP showed a sudden drop. This may be due to the fact that when the fracture occurs in the specimen, PVA fibers are mainly debonded and pulled out, and POM and PP fibers are mainly broken.

3.4. Shrinkage

The shrinkage rate of each group of specimens at different curing ages was measured, and the shrinkage data results were counted. The specific shrinkage data are shown in Figure 4.



(**a**) (**b**)

Figure 4. Shrinkage of geopolymer mortar repair material: (**a**) Fiber incorporation is 1.0%; (**b**) Fiber incorporation is 2.0%.

Figure 4 shows that the variation of fiber incorporation and type affects the shrinkage properties of the geopolymer mortar repair material. With the growth of the curing age, the slope of the shrinkage curve of each group of specimens decreases and gradually tends to 0. When the age of curing is from 5 days to 9 days, the slope of the shrinkage curve of each group of specimens is larger, and the shrinkage rate grows rapidly. When the age of curing is from 14 days to 28 days, the slope of the shrinkage curve of each group of specimens is smaller, and the shrinkage rate grows slowly. This is mainly because the shrinkage of the geopolymer is a continuous process, with larger shrinkage in the early stages and smaller shrinkage in the later stages, eventually stabilizing. The incorporation of PVA fibers reduces the shrinkage of the geopolymer, and the shrinkage of the geopolymer tends to decrease as the amount of fiber incorporation increases. The shrinkage of A1 and A4 is reduced by 3.26% (all percentages in 3.3 represent ratios and do not represent shrinkage rate) and 9.31%, respectively, compared to A0. The effect of POM and PP fibers on the shrinkage of the geopolymer is opposite to that of PVA fibers: the shrinkage of the geopolymer tends to increase with the increase in fiber incorporation. The shrinkage of A5 is 16.97% greater than that of A2, and that of A6 is 19.32% greater than that of A3.

When the fiber incorporation is the same, different types of fibers have different effects on the shrinkage of the geopolymer. When the amount of fibers incorporated is the same, and both are 1.0%, the incorporation of PVA fiber, POM fiber, and PP fiber all reduce the shrinkage of the geopolymer, among which the POM fiber has the most obvious effect on the reduction in the shrinkage of the geopolymer. Compared with A0, the shrinkage rates of A1, A2, and A3 are reduced by 3.26%, 10.67%, and 9.36%, respectively. As the fiber incorporation increases from 1.0% to 2.0%, the shrinkage of the geopolymer incorporated with POM fibers and with PP fibers increases, and the shrinkage of the geopolymer incorporated with PVA fibers decreases. When the amount of fibers incorporated is the same, and both are 2.0%, the PVA fiber has the most obvious effect on the reduction in the shrinkage of the geopolymer. The shrinkage of A4 is 13.21% and 16.15% smaller than that of A5 and A6, respectively.

The incorporation of PVA fibers reduces the shrinkage of the geopolymer. This is mainly due to the good chemical bonding at the interface between the PVA fibers and the geopolymer matrix, resulting in a strong adhesion between the two. When 1.0%

PP fibers or POM fibers are incorporated, the bonding of the fibers to the geopolymer will help to restrain cracks and inhibit shrinkage. When incorporating 2.0% PP or POM fibers, the higher fiber incorporation may result in the formation of a denser fiber network structure, which may cause the molecules to be more tightly linked during the curing process, thereby increasing shrinkage. The shrinkage rate of geopolymer mortar repair materials in all groups is less than 0.25%, which is in line with the requirements of JC/T 2381-2016, People's Republic of China building materials industry standard, and has a relatively small impact on building repair. The results show that the shrinkage properties of the geopolymer mortar repair material are better when 1% POM fibers are incorporated.

3.5. Bonding Properties

It is extremely important to have good bonding properties between the repair material and the surrounding building in order to maximize the mechanical properties of the repair material. The specific data obtained from the experiment are shown in Table 9 and Figure 5. Table 9 lists the flexural strength of each group of repaired specimens. The bad data are removed according to the National Standard GB/T 17671-20219 of the People's Republic of China, and the arithmetic mean value of each group of data is calculated as shown in Figure 5.

Table 9. Flexural strength of repaired specimens.

Repaired Specimen	**B0**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**
Fiber incorporation amount (%)	0	1.0% PVA	1.0% POM	1.0% PP	2.0% PVA	2.0% POM	2.0% PP
	4.0	4.3	4.4	4.4	4.8	5.0	4.8
Flexural strength (MPa)	4.3	4.6	4.3	4.6	3.9	4.7	4.5
	3.9	4.5	4.4	2.9	4.8	4.9	4.6

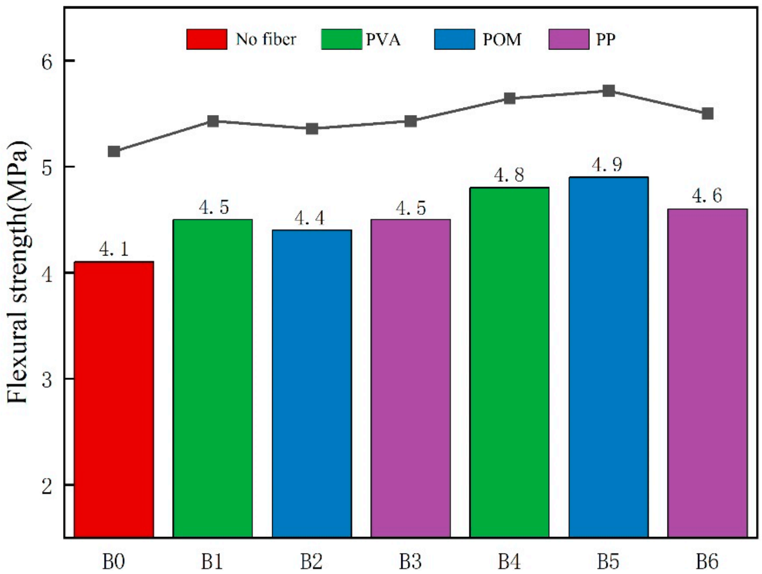


Figure 5. Flexural strength of repaired specimens.

In all fractured repaired specimens, the fracture surface of each specimen was located near the bonding surface of the cement mortar and the repair material. Therefore, the flexural strength of the repaired specimens was used to express the bonding properties of the repaired material to the cement mortar. The better the bonding properties of the repair material, the greater the flexural strength of the repaired specimen. The fracture surface of the cement mortar portion of each specimen contained different areas of geopolymer and a few fibers. This was mainly because the repair material was only partially bonded with the cement mortar and not completely bonded on the bonding surface. Thus, the bonding surface was the weak surface of the whole repaired specimen, and the fracture occurred near the bonding surface. The fracture surface of the cement mortar section had geopolymers and fibers, indicating that the fracture occurred on the geopolymer mortar repair material, and therefore, the bond strength of the bonding area on the fracture surface was greater than the flexural strength of the geopolymer mortar repair material. A comprehensive analysis of the flexural strength and specimen fracture surfaces showed that the bonding properties of the geopolymer mortar repair material were satisfactory and could meet the repair requirements of the building.

From Figures 5 and 6, it can be seen that the fiber incorporation has a greater effect on the flexural strength of the repaired specimens. The flexural strength of repaired specimens is related to the bonding area of the bonding surface and the mechanical properties of the geopolymer mortar repair material. Compared to the B0 fracture surface in Figure 6, all the other specimens have fibers entrapped in the fracture surface. The reason for this may be that the groups of repair specimens from B1 to B6 have incorporated fibers. When the fracture occurs in the area of the geopolymer mortar repair material, the fibers can withstand the load and prevent the premature destruction of the geopolymer matrix, thus enhancing the flexural strength of the repaired specimens.

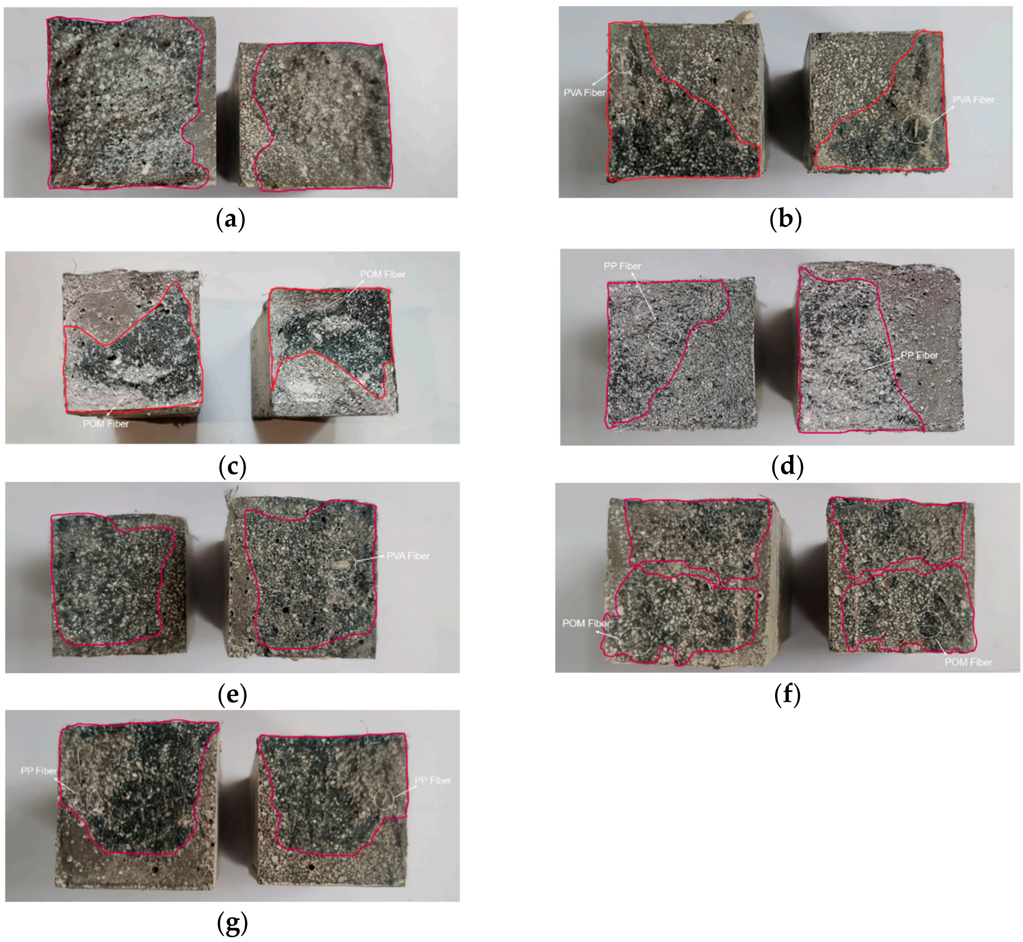


Figure 6. Fracture surface of repaired specimens: (**a**) B0; (**b**) B1; (**c**) B2; (**d**) B3; (**e**) B4; (**f**) B5; (**g**) B6.

It can be seen from Figure 5 that the flexural strength of the repaired specimens gradually increases with the increase in fiber incorporation. Compared with B0, the flexural strength of B1, B2, and B3 increases by 9.76%, 7.32%, and 9.76%, respectively, and the flexural strength of B4, B5, and B6 increases by 17.07%, 19.51%, and 12.19%, respectively. From all the fracture surfaces in Figure 6, it can be seen that the bonding area of the repaired specimens incorporated with 1.0% fibers is about 50% to 60% of the fracture surface area, and the bonding area of the repaired specimens incorporated with 2% fibers is about 70% to

80% of the fracture surface area. Combined with the analysis of the mechanical properties of the geopolymer, the mechanical properties of the geopolymer decrease with the increase in fiber incorporation, but the flexural strength of the repaired specimens increases with the increase in fiber incorporation. Thus, the increase in flexural strength of the repaired specimens depends on the increase in the bonding area of the fracture surface. The bonding area increases with the increase in fiber incorporation, further making the flexural strength of the repaired specimens increase with the increase in fiber incorporation.

The bonding test results show that the bonding properties of the geopolymer mortar repair material incorporated with 2.0% POM fibers are superior.

3.6. Micro Characterization

Figure 7 shows the XRD spectra of the geopolymer matrix and the PDF cards of $CaCO_3$, Al_2O_3, and hydrated calcium silicate (C–S–H) gel. The main components of the geopolymer matrix are $CaCO_3$, Al_2O_3, and C–S–H gel, among which Al_2O_3 is mainly from the raw materials in the early stage, and the hydration products of the gelling materials are mainly $CaCO_3$ and C–S–H gel. The peaks observed for C–S–H gels are about 29.36° (2θ) and 31.47° (2θ), which are the same as the results of Guo et al. [37]. The C–S–H gel has an enhancing effect on the strength of the geopolymer and fills the capillary pores of the geopolymer, resulting in a tighter structure. While the strength is increased accordingly, the corrosion resistance of the geopolymer is improved, so the geopolymer has the macroscopic characteristics of good mechanical properties and corrosion resistance.

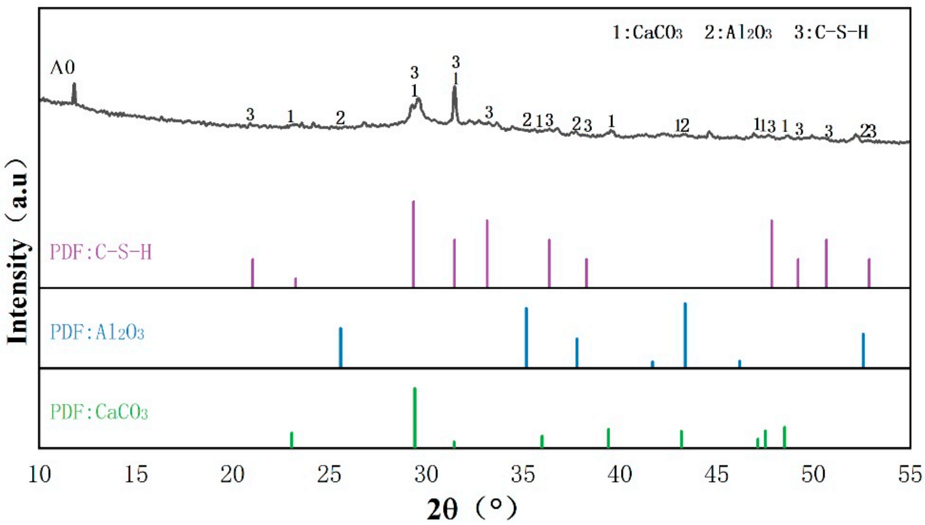


Figure 7. XRD pattern of the geopolymer matrix.

The fractured specimens were scanned using electron microscopy. The SEM images obtained are shown in Figure 8. Figure 8a shows that there are a large number of microcracks in the geopolymer matrix, and the expansion of microcracks is accelerated under load, so the geopolymer is brittle. These microcracks are caused by the shrinkage of the geopolymer. From Figure 8b–d, it can be seen that all three types of fibers have geopolymer particles adhered to their surfaces, indicating that bond strength exists between the fibers and the geopolymer. When the specimen is in the yield stage or fractured, the bond strength between the fibers and the geopolymer prevents the fibers from being pulled out to a certain extent, which in turn triggers a bridging effect of the fibers to protect the geopolymer matrix. PVA fiber had far more geopolymer particles adhering to its surface than POM and PP fibers, indicating a stronger bond between the PVA fiber and the geopolymer matrix. This explains the most obvious toughening effect of the PVA fibers and also shows that the interface between the PVA fibers and the geopolymer matrix has good chemical bonding properties that reduce the shrinkage of the geopolymer. As shown in Table 2, the tensile strength of the PVA fibers is high, and Figure 8b shows that the PVA fibers have broken, further proving that the bond strength between the PVA fibers and the geopolymer matrix is satisfactory. From Figure 8c, it can be seen that the fiber surface has the least amount of geopolymer particles, and the surface is scratched. This indicates that the bond strength between the POM fibers and the geopolymer matrix is weak, and the bond between the two is not sufficient, resulting in the POM fibers pulling out and the bridging effect not being fully developed, leading to damage to the geopolymer matrix around the fibers. As shown in Figure 8d, compared to POM fibers, the geopolymer matrix near PP fibers is more intact, with rougher fiber surfaces and more geopolymer particles adhered to the fibers. This indicates that the greater bond strength and friction generated between the PP fibers and the geopolymer matrix enables the bridging effect of the fibers to be more fully exploited to protect the surrounding geopolymer matrix. At the same time, the greater bond strength allows PP fibers to consume more energy during breaking, debonding, and pulling out, which explains the better toughening effect of PP fibers than POM fibers.

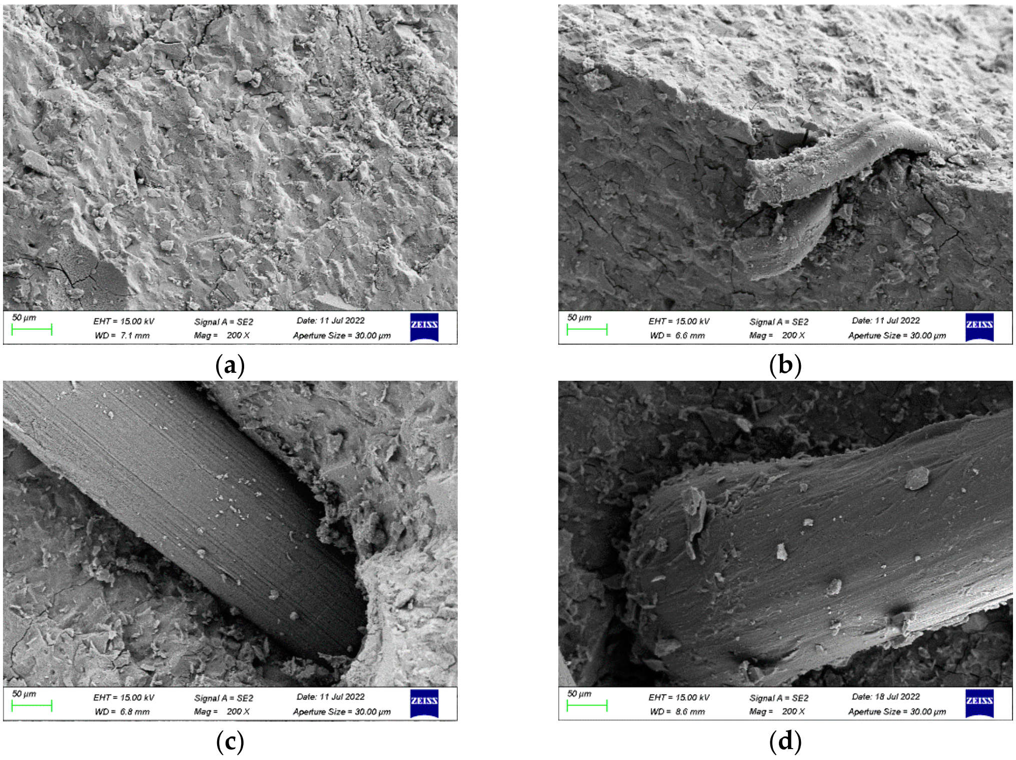


Figure 8. SEM images of geopolymer mortar repair material: (**a**) Geopolymer matrix; (**b**) Geopolymer mortar repair material incorporated with PVA fiber; (**c**) Geopolymer mortar repair material incorporated with POM fiber; (**d**) Geopolymer mortar repair material incorporated with PP fiber.

The results show that the incorporation of PP fibers into the geopolymer mortar repair material has better mechanical properties than the incorporation of POM fibers. The reason for this is that PP fibers have a stronger bond to the geopolymer matrix, which creates more friction during debonding and pull-out and can withstand more loads. The mechanical properties of the geopolymer mortar repair material incorporated with PVA fibers are the worst, mainly because of its poor workability, so a large number of pores are generated during the preparation process, reducing its mechanical properties.

4. Conclusions

In this study, the effect of different fibers on the geopolymer mortar repair material was investigated. The incorporation of fibers not only enhanced the toughness of the geopolymer but also had different degrees of influence on the shrinkage and bonding properties. The conclusions can be drawn as follows:

1. The incorporation of fibers enhances the compressive strength and reduces the flexural strength. The flexural strength of the geopolymer mortar repair material decreases, and the compressive strength increases with the increase in fiber incorporation. A comprehensive analysis of flexural and compressive strengths shows that the mechanical properties of the geopolymer mortar repair material are relatively better when 1.0% PP fibers are incorporated;
2. The incorporation of fibers enhances the toughness of the geopolymer. The toughness of the geopolymer increases with the increase in fiber incorporation. A comprehensive analysis of the load-deflection curves and toughness indexes shows that the toughening effect of PVA fibers is the best and the toughening effect of POM fibers is the worst;
3. The shrinkage of the geopolymer mortar repair material has relatively little effect on the building repair. As the fiber incorporation increases, PVA fiber reduces the shrinkage of the geopolymer, and POM fiber and PP fiber increase the shrinkage of the geopolymer. The results show that the shrinkage of the geopolymer mortar repair material is better when 1% POM fibers are incorporated;
4. The fracture surface of the repaired specimen occurs in the geopolymer portion, so the geopolymer mortar repair material has good bonding properties and can be used for building repair work. The increase in flexural strength of the repaired specimens depends on the bonding area of the fracture surface, which increases with the amount of fiber incorporation;
5. By XRD analysis, the hydration products of the geopolymer matrix can be detected as $CaCO_3$ and C–S–H gels. From SEM images, the bond strength of PVA fibers to the geopolymer matrix is maximum; compared to POM fibers, PP fibers have a rougher surface, more geopolymer particles attached, and greater fiber-to-matrix bond strength and friction.

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