# Effect of fibre type and content on performance of bio-based concrete containing heat-treated apricot shell

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ORIGINAL ARTICLE

# Effect of fibre type and content on performance of bio-based concrete containing heat-treated apricot shell

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**Abstract** The heat-treated apricot shell can be utilized as coarse aggregates for producing sustainable bio-based lightweight concrete with good compressive strength but poor tensile strength. In order to improve the tensile properties of apricot shell concrete (ASC), the effects of polypropylene (PP) fibre, glass (G) fibre and basalt (B) fibre at various volume fractions ($V_f$) (0.25%, 0.5% and 0.75%) on the performance of ASC were investigated. The results indicated that the fibre type had no significant effect on the physical properties of ASC such as slump, density, water absorption and permeable porosity. However, the slump of ASC decreases with an increase in fibre content. The B fibre has a better improvement in mechanical properties than the PP fibre and G fibre thanks to the better elastic modulus and tensile strength. When the $V_f$ was 0.5%, the compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of ASC reinforced with B fibre were increased by 16.7%, 29.1%, 29.2%, and

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18.1%, respectively, compared to ASC without any fibres. The magnesium sulfate attack results showed that the incorporation of the B fibre decreased the mass loss and compressive strength of ASC exposed to a $MgSO_4$ solution for 6 months because the fibre arrested the microcracks caused by the expansive stress. It is concluded that the mechanical properties of bio-based ASC and its resistance to magnesium sulfate attack can be significantly improved by incorporating 0.5% B fibre.

**Keywords** Lightweight concrete · Heat-treated apricot shell · Polypropylene fibre · Glass fibre · Basalt fibre · Tensile strength · Magnesium sulfate attack

## 1 Introduction

With the huge demand for concrete and adapting to sustainable building material requirements, many agricultural wastes such as bamboo, wood dust, oil palm shell, peach shell, seashell and miscanthus, etc. have been widely used in concrete [1]. Due to the porosity and lightweight properties, they are very suitable for the production of bio-based lightweight aggregate concrete (LWAC) [2]. The addition of bio-based materials leads to better heat insulation and sound absorption of concrete, compared to normal weight concrete [3]. Besides, the replacement of coarse aggregates with agricultural wastes not only reduces the cost of concrete but also decreases the consumption of aggregates and reuses wastes [4]. Therefore, in the construction industries, the concept of sustainable development motivates agricultural wastes to replace raw material resources, which results in environment-friendly and sustainable building materials [5].

Apricot (*Prunus armeniaca L.*) is a common fruit that is widely cultivated in some countries, such as China, Turkey, Italy, Iran, Uzbekistan etc. [6]. In 2017, the planting area of apricot in the world is approximately $5.4 \times 10^5$ ha, with an annual output of about $4.3 \times 10^6$ tons [7]. In China, the production of apricot was $2.7 \times 10^6$ tons in 2014 [8]. In addition to being directly used as a fruit, most apricots are used for processing as juices, canned fruit and sweetmeat. Therefore, a lot of apricot shell (AS) are discarded as garbage in fruit processing plants. Recently, in order to recycle the AS and improve the economic value, it has been investigated for soil conditioners, blended fuels and activated carbon [9–11]. Previous studies [12, 13] showed that the AS is suitably used as an alternative lightweight aggregate for bio-based LWAC because of good rigidity and lightweight properties of the AS.

However, similar to conventional concrete, plain apricot shell concrete (ASC) is a typical brittle material with low tensile strength and low energy absorption capacity [14]. At the same strength, the tensile strength of LWAC is only 0.8–0.85 of that of normal weight concrete [15]. Due to the high brittleness of concrete, an audible noise can be heard because of cracks produced before reaching the ultimate loading during the compressive test [16]. Moreover, due to the porosity and degradation characteristics of bio-based aggregates, plain ASC is susceptible to having microscopic cracks, which allows harmful chemicals such as acid, sulfate and chloride ion, and other substances to enter the concrete matrix and react with hydrated products of cement, which speeds up the deterioration of concrete and causes durability problems such as chemical attack, shrinkage and thermal deformation, etc. [17]. Considering the high-performance requirements of contemporary building structures, it is necessary to make bio-based ASC with better mechanical strength and durability by hindering the development of cracks and reducing the brittleness of concrete.

In the past few decades, many researches have demonstrated that adding fibres in concrete has an important effect on the performance of concrete, especially for improving the tensile strength, post-cracking capacity, impact resistance and durability of concrete [18, 19]. The formation of fibre bridging in reinforced concrete, which arrests and bridges the cracks and restraint the formation and propagation of cracks and can improve the tensile performance and the load-carrying capacity [20]. Among various fibres, polypropylene (PP) fibre, steel fibre and glass (G) fibre are the most popular fibres used in concrete for increasing the tensile strength properties. However, the high specific gravity of the steel fibre severely limits its application in LWAC because of the requirements for low density [21]. Compared to the steel fibre, PP and G fibre is relatively economical and lightweight, which is more suitable to be applied in LWAC [18]. However, the chemical degradation of the fibre leads to rapid strength loss when the fibre is exposed to the high alkalinity of the cementitious composites [22]. Rostami et al. [22] reported that steel fibre, carbon fibre and PP fibre present better resistance to deterioration than G fibre when in contact with moisture, alkalis or other ingredients of chemical admixtures. However, CaO, $Al_2O_3$ and $SiO_2$ and other polymeric compounds in G fibre act as an additive to increase the adhesion and binding of concrete [23]. Besides mechanical properties, the fibre reinforced concrete also exhibited good resistance to aggressive environmental exposures [24], for example, the addition of PP fibre in concrete decreases the degradation of pre-yield stiffness of reinforced concrete beam and the corrosion of steel [25]. The effect of sulfates on components of concrete is one of the most common chemical attacks, owing to the chemical reaction between sulfate ions and the hydrated products of cement (C–S–H), and eventually, the formation of gypsum and ettringite leads to the deterioration of concrete [17]. The basalt (B) fibre is currently used as reinforcing materials due to high surface free energy and polar component [20], which is beneficial to improve the resistance of concrete to magnesium sulfate attack [24] and the crack resistance by reducing the cracks in the interfacial transition zone (ITZ) [26]. Therefore, the addition of fibres to concrete not only improves the mechanical strength of concrete but also increases its resistance to chemical attacks. So far, there is no literature on investigating the effects of fibre type and content on the mechanical properties and resistance to magnesium sulfate attack of ASC.

In order to improve the tensile properties of ASC, the heat-treated AS was used as lightweight aggregates for the manufacture of bio-based ASC in this study. This research focused on studying the effects of three types of fibres with various volume fractions ($V_f$) on the physical properties (workability, density, water absorption and permeable porosity), mechanical properties (compressive strength, splitting tensile strength, flexural strength and modulus of elasticity) of ASC. The three types of fibres were polypropylene fibre (PP), glass fibre (G) and basalt fibre (B), and the $V_f$ for each fibre was designed as 0.25%, 0.5% and 0.75%, respectively. The resistance to magnesium sulfate attack after 6 months of exposure was evaluated. The optimum fibre type and content for ASC were obtained based on the results of this study.

## 2 Materials and methods

### 2.1 Materials

#### *2.1.1 Aggregates*

The heat-treated apricot shell (AS) can significantly enhance the mechanical performance of apricot shell concrete (ASC) because the thermal decomposition of cellulose, hemicellulose and lignin significantly reduced the swelling-shrinkage and increased the degradation resistance, dimensional stability and surface quality of the AS [4, 27]. Therefore, the heat-treated AS was chosen as coarse aggregates applying the pyrolysis process reported by Wu et al. [4]. The particle size distribution and physical properties of the AS are presented in Fig. 1 and Table 1, respectively. According to the requirements of the Chinese Lightweight Aggregate Standard (GB/T 17431.1-2010 [28]), the minimum crushing aggregate strength of artificial lightweight aggregates with a bulk density of 500–600 kg/m$^3$ is 2.0 MPa. Heat-treated AS has a crushing aggregate strength of 3.2 MPa, which hence meets the strength requirements of lightweight aggregates. The microscopic morphology of the AS was observed by scanning electron microscope (SEM), as shown in Fig. 2. The heat-treated AS was porous and lightweight, which resulted in high water absorption of AS [4]. The AS was soaked in water for 24-h and then air-dried at room temperature until the saturated surface was dried prior to application.

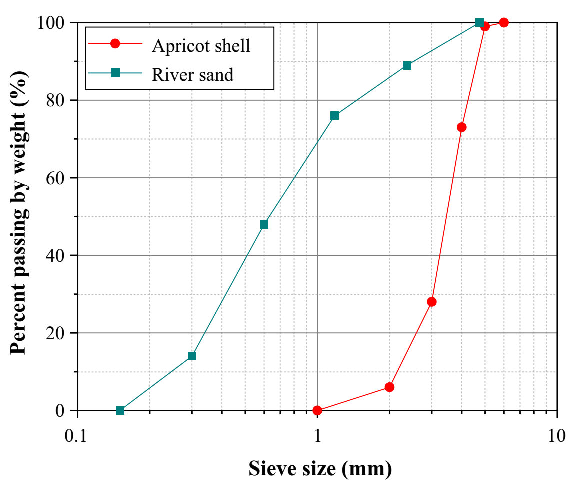


**Fig. 1** Particle size distribution of apricot shell and river sand

**Table 1** The properties of apricot shell and river sand

| Materials | Density (g/cm$^3$) | Fineness modulus | Bulk density (kg/m$^3$) | 24-h water absorption (%) | Crushing aggregate strength (MPa) | Shape |
|---|---|---|---|---|---|---|
| Apricot shell | 1.32 | 5 | 575 | 14.2 | 3.2 | Flaky |
| River sand | 2.58 | 2.89 | 1569 | 1.2 | – | Rounded |

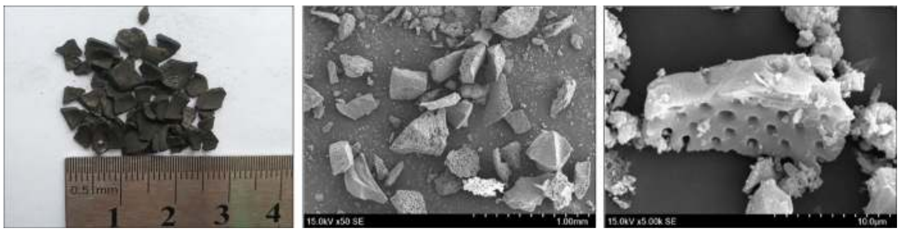

**Fig. 2** Heat-treated apricot shell and its microscopic image

Commercial river sand was used for fine aggregates. The fineness modulus of the river sand was 2.89, as shown in Table 1, which belongs to medium sand according to ASTM C33-03 [29].

### *2.1.2 Cement, water and superplasticizer*

Type I 42.5 grade Portland commercial cement was used as binder. Tap water was used for all mixtures. The commercial superplasticizer (SP) complied with the specification of concrete admixture standard (GB/8076-2008 [30]) was used to improve workability. The dosage of SP was 1 wt.% of the cement content.

### *2.1.3 Fibres*

The properties of fibres are shown in Table 2. Three types of fibres were used, including polypropylene (PP) fibre, glass (G) fibre and basalt (B) fibre, as presented in Fig. 3.

## 2.2 Mix proportion and specimen preparation

In this study, all mixtures had the same cement, AS, sand, water and SP content, which were 550 kg/m$^3$, 380 kg/m$^3$, 780 kg/m$^3$, 220 kg/m$^3$ and 5.5 kg/m$^3$, respectively. Afterwards, the fibre with different volume fraction ($V_f$) was added to the mixture. Considering high $V_f$ of fibres tended to agglomerate in the mixtures and caused the workability problems of concrete [31], the $V_f$ of three types of fibres was set to 0.25%, 0.5% and 0.75%, respectively. A concrete without any fibre was used for the control specimen. The mix proportions of concrete are shown in Table 3.

The specimen preparation was carried out according to technical specification for lightweight concrete (JGJ-51-2002 [32]). Firstly, AS, sand and cement were dry mixed for 0.5 min. Then, fibres were added and dispersed in the mix for 0.5 min. Finally, water and SP were poured into the mixture and mixed for 2.5 min. After that, the workability test was carried out before

**Table 2** The properties of three types of fibres

| Fibre type | Length (mm) | Diameter (μm) | Density (g/cm$^3$) | Tensile modulus (GPa) | Tensile strength (MPa) | Elongation at break (%) |
|---|---|---|---|---|---|---|
| PP fibre | 19 | 25–40 | 0.91 | 3.5 | 550 | 60–90 |
| G fibre | 22 | 10 | 2.54 | 75 | 3040 | 2.5 |
| B fibre | 24 | 15 | 2.65 | 93–110 | 4150–4800 | 3.1 |

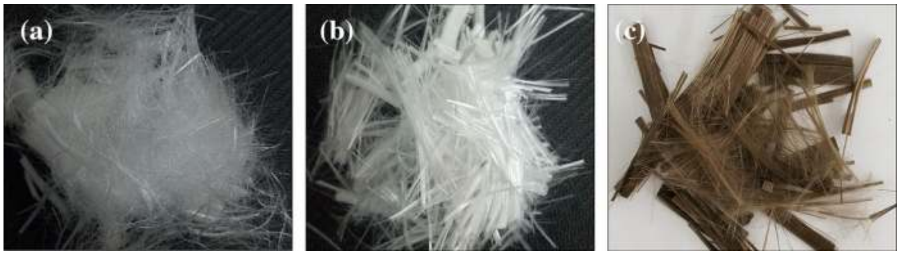


**Fig. 3** **a** Polypropylene fibre, **b** Glass fibre and **c** Basalt fibre

**Table 3** The mix proportions of concrete

| Mix code | Cement (kg/m$^3$) | AS (kg/m$^3$) | Sand (kg/m$^3$) | Water (kg/m$^3$) | SP (kg/m$^3$) | PP fibre (vol.%) | G fibre (vol.%) | B fibre (vol.%) |
|---|---|---|---|---|---|---|---|---|
| Control | 550 | 380 | 780 | 220 | 5.5 | 0 | 0 | 0 |
| PP/25 | 550 | 380 | 780 | 220 | 5.5 | 0.25 | 0 | 0 |
| PP/50 | 550 | 380 | 780 | 220 | 5.5 | 0.50 | 0 | 0 |
| PP/75 | 550 | 380 | 780 | 220 | 5.5 | 0.75 | 0 | 0 |
| G/25 | 550 | 380 | 780 | 220 | 5.5 | 0 | 0.25 | 0 |
| G/50 | 550 | 380 | 780 | 220 | 5.5 | 0 | 0.50 | 0 |
| G/75 | 550 | 380 | 780 | 220 | 5.5 | 0 | 0.75 | 0 |
| B/25 | 550 | 380 | 780 | 220 | 5.5 | 0 | 0 | 0.25 |
| B/50 | 550 | 380 | 780 | 220 | 5.5 | 0 | 0 | 0.50 |
| B/75 | 550 | 380 | 780 | 220 | 5.5 | 0 | 0 | 0.75 |

casting the specimen. The fresh concrete was cast into the oiled mould and compacted with a vibrating table. After that, the surface of specimens was covered with a plastic film to avoid moisture loss and stored in the laboratory. After approximately 24 h, they were demoulded and stored in the curing chamber with a relative humidity of 95 ± 5% and a temperature of 20 ± 2 °C until the test age.

## 2.3 Test methods

The workability and density of all mixes were determined according to ASTM C143/C143M-12 [33] and ASTM C138/C138-14 [34], respectively. The water absorption and permeable porosity were determined based on ASTM C642-13 [35]. The mechanical properties of all mixes were determined based on GB/T 50080-2016 [36] (Fig. 4a–c).

In this study, different concentrations (4%, 8% and 12%) of magnesium sulfate ($MgSO_4$) solution were used to simulate the coupled magnesium and sulfate attack environment to assess the degradation of ASC in the $MgSO_4$ solution according to the ASTM C267-01 [37]. The 28-day saturated specimen was immersed in $MgSO_4$ solution with different concentrations. To ensure the concentration of the $MgSO_4$ solution, the $MgSO_4$ solution was replaced by a new $MgSO_4$ solution monthly. The changes in the mass loss of specimens and compressive strength loss exposed by the $MgSO_4$ solution after 6 months were recorded and calculated according to the ASTM C267-01 [37] (Fig. 4d).

# 3 Results and discussion

## 3.1 Physical properties

### *3.1.1 Workability*

As shown in Fig. 5, the slump of apricot shell concrete (ASC) decreased with an increase in fibre volume fraction ($V_f$) regardless of fibre types. The addition of fibres from 0 to 0.75% for polypropylene (PP) fibre,

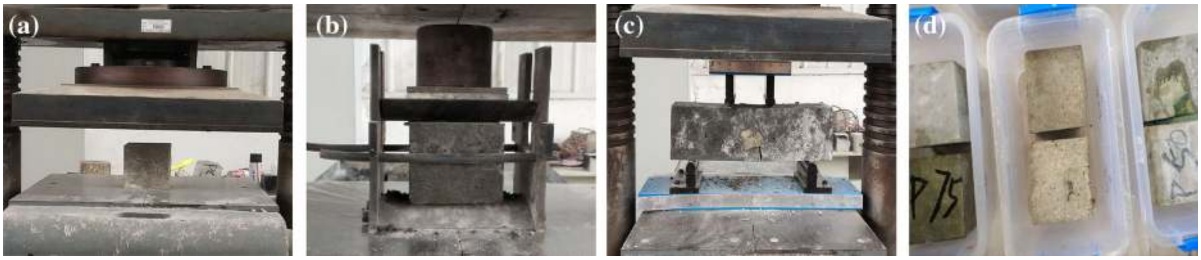


**Fig. 4** Test details of samples **a** Compressive test, **b** Splitting tensile test, **c** Flexural test and **d** Magnesium sulfate test

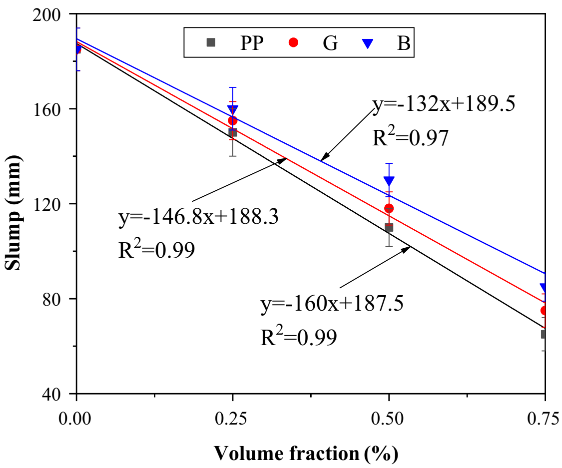


**Fig. 5** Effects of fibre volume fraction on the slump

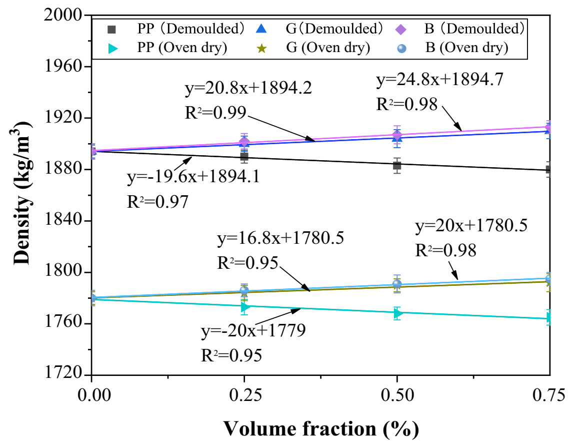


**Fig. 6** Effects of fibre volume fraction on density

glass (G) fibre and basalt (B) fibre decreased the slump by approximately 64.9%, 59.5% and 54.1%, respectively. The negative effect of the PP, G and B fibres on workability was observed in previous studies such as oil palm shell concrete [31], ceramic concrete [18], geopolymer concrete [38]. This is because fibres with a high surface area tend to absorb more cement paste to wrap around, increase the viscosity and results in low slump [39]. Moreover, the large surface area of short fibres and high fibre content produced lower workability [31]. In this study, the hydrophilic properties of PP fibre resulted in a lower slump of PP fibre reinforced ASC.

### *3.1.2 Density*

The effects of fibre volume fraction on the density of ASC are presented in Fig. 6. The results indicated that with $V_f$ increasing from 0 to 0.75%, PP fibre slightly decreased the density while G fibre and B fibre slightly increased the density. At $V_f$ of 0.75%, PP fibre reinforced ASC achieved the lowest density while B fibre reinforced ASC showed the highest density. This is attributed to the specific density of 0.91 g/cm$^3$ of the PP fibre which is much lower than that of G fibre (2.54 g/cm$^3$) and B fibre (2.65 g/cm$^3$). Although low-density PP fibres are more advantageous for lightweight aggregate concrete (LWAC) in terms of density, high content of PP fibre tends to entrap more air voids into the fresh mixture, resulting in the porosity of the concrete and the negative impact on the mechanical properties [40]. The B fibre slightly increased the density of ASC because B fibre absorbs some of the water for hydration, which reduces water content during mixing, resulting in a denser mortar and a slight increase in density [41]. This also was observed in G fibre reinforced concrete reported by Sayyad and Patankar [42]. The oven-dry density of all ASCs varied between 1765 kg/m$^3$ and 1795 kg/m$^3$, respectively, which meets the density requirements for LWAC (EN206-1).

#### 3.1.3 Water absorption and permeable porosity

As shown in Fig. 7, the addition of fibres from 0 to 0.5% decreased the water absorption and permeable porosity of ASC. The phenomenon of adding low fibre content decreased water absorption and porosity was also reported in previous studies due to the pore-blocking effect of the fibre [43, 44] and good adhesion and densification of cement paste [45]. However, when $V_f$ varied from 0.5 to 0.75%, a slight increase in the water absorption and the permeable porosity of ASC could be observed. This may be due to the formation of air voids caused by high fibre content also leads to the diffusion of water [44]. Therefore, only a suitable amount of fibre is added to concrete, which is advantageous for reducing water absorption and permeable porosity. In this study, at a fibre content of 0.5%, the ASC obtained the lowest water absorption and permeable voids.

### 3.2 Mechanical properties

#### 3.2.1 Compressive strength

The mechanical properties of ASC are shown in Table 4. The results indicated that the incorporation of fibres improved the compressive strength of ASC with a relatively low increase rate. In this study, the compressive strengths of PP/50, G/50 and B/50 at the age of 28 days were 43.4 MPa, 44.2 MPa and 44.7 MPa, respectively, which were improved by 13.3%, 15.4% and 16.7%, respectively, compared to the ASC without any fibres. During the uniaxial compressive test, the cracks firstly occur around the lightweight aggregate when the transverse tensile strain excess the ultimate tensile strain of lightweight aggregate. With further increasing stress, cracks penetrate through the lightweight aggregate and propagate to the mortar, and finally, the failure occurs and the ultimate compressive strength is obtained [19]. The incorporation of fibres increasing the compressive strength in the concrete matrix is also observed in previous studies [46, 47]. Plagué et al. [47] reported that the fibre controls the microcrack formation and leads to the delay of failure, increasing the ultimate strength, and also strongly participate to carry the load on the post-peak phase. Moreover, the blunting, blocking and diverting of cracks allow the fibre-reinforced concrete to withstand additional compressive load [48]. The addition of fibres also changes the failure mode of concrete from brittle failure to plastic failure. This phenomenon becomes more obvious as the fibre content increases, because the fibre effectively prevents the propagation of cracks and restricts the convergence of cracks, and eventually adsorbing more destructive energy [46].

As shown in Fig. 8, when the $V_f$ increased from 0.5 to 0.75%, the compressive strength of ASC decreased. This is attributed to excessive fibre content, having an adverse effect on compressive strength [16, 19, 21]. The results also showed that the enhancement in

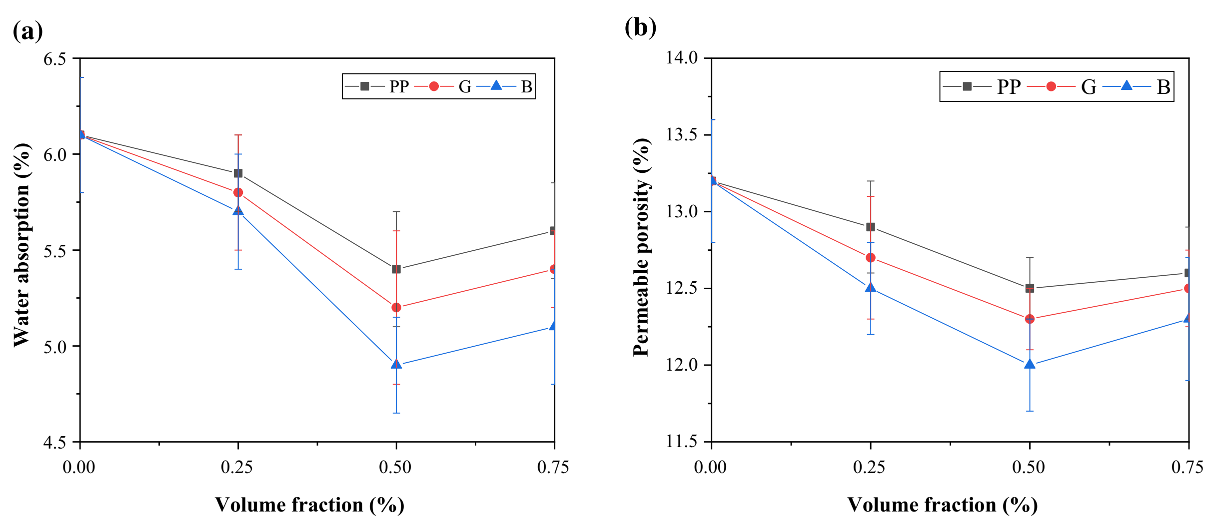


**Fig. 7** Effects of fibre volume fraction on water absorption and permeable porosity

**Table 4** Mechanical properties of the concretes

| Mix code | Compressive strength (MPa) | | | | Splitting tensile strength (MPa) | Flexural strength (MPa) | Modulus of elasticity (GPa) |
|---|---|---|---|---|---|---|---|
| | 3-day | 7-day | 28-day | 56-day | | | |
| Control | 28.1 ± 1.1 | 33.7 ± 0.9 | 38.3 ± 1.2 | 39.5 ± 0.9 | 3.23 ± 0.16 | 5.51 ± 0.24 | 13.8 ± 0.3 |
| PP/25 | 29.6 ± 1.3 | 37.2 ± 1.4 | 40.2 ± 1.2 | 43.4 ± 1.4 | 3.47 ± 0.18 | 5.79 ± 0.26 | 14.3 ± 0.4 |
| PP/50 | 31.1 ± 1.5 | 38.0 ± 1.2 | 43.4 ± 1.0 | 45.8 ± 1.3 | 3.76 ± 0.21 | 6.32 ± 0.24 | 15.4 ± 0.3 |
| PP/75 | 30.1 ± 1.2 | 37.6 ± 1.2 | 42.2 ± 0.9 | 44.5 ± 1.1 | 3.60 ± 0.17 | 6.09 ± 0.20 | 14.9 ± 0.5 |
| G/25 | 30.1 ± 1.2 | 35.8 ± 1.3 | 40.7 ± 1.1 | 42.3 ± 1.0 | 3.74 ± 0.20 | 6.21 ± 0.19 | 14.6 ± 0.4 |
| G/50 | 30.5 ± 0.9 | 37.4 ± 0.8 | 44.2 ± 1.2 | 46.4 ± 1.1 | 4.03 ± 0.19 | 6.97 ± 0.25 | 16.1 ± 0.3 |
| G/75 | 29.7 ± 1.1 | 36.9 ± 1.2 | 42.4 ± 1.4 | 44.8 ± 1.2 | 3.84 ± 0.18 | 6.53 ± 0.27 | 15.5 ± 0.4 |
| B/25 | 31.2 ± 1.3 | 36.5 ± 1.1 | 41.5 ± 1.2 | 44.2 ± 0.9 | 3.85 ± 0.20 | 6.41 ± 0.22 | 15.8 ± 0.5 |
| B/50 | 32.4 ± 1.2 | 38.4 ± 1.1 | 44.7 ± 0.8 | 46.8 ± 1.0 | 4.17 ± 0.19 | 7.12 ± 0.25 | 16.3 ± 0.4 |
| B/75 | 31.5 ± 1.4 | 37.7 ± 1.2 | 43.2 ± 1.1 | 45.3 ± 1.0 | 4.06 ± 0.17 | 6.84 ± 0.23 | 16.1 ± 0.4 |

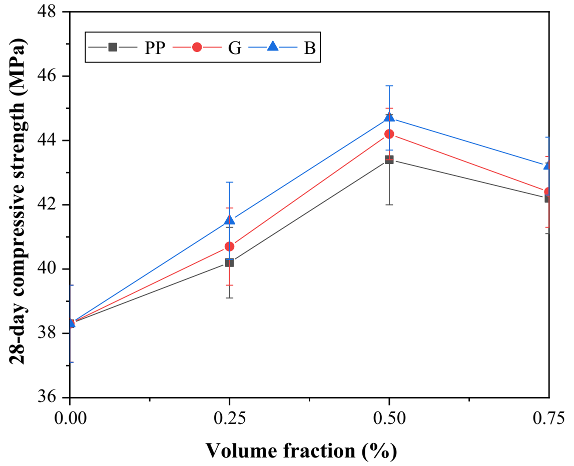


**Fig. 8** Effects of fibre volume fraction on 28-day compressive strength

compressive strength of B fibre reinforced ASC was better than that of G fibre and PP fibre. This may be due to the elastic modulus and tensile strength of B fibre that are higher than that of PP fibre and G fibre, and thus it has better restrain effect to crack propagation [26]. In addition, the small-diameter fibres had higher efficiency in bridging microscopic cracks and increasing compressive strength compared to macroscopic fibres [39]. The diameter of PP fibre was larger than that of B fibre, which increased the pores of concrete by the air-entraining effect of fibre and reduced the bonding ability between the PP fibre and the matrix interface compared to B fibre [49].

For bio-based LWAC, the weak bond between the bio-aggregate and the mortar is the main reason for the low mechanical strength due to the presence of organic matter in bio-based aggregates. Microscope image of concrete containing PP fibre is shown in Fig. 9, which indicated the interfacial transition zone (ITZ) between the heat-treated AS and the mortar was tightly bonded together, and no obvious microcracks were observed. Previous studies also reported that heat-treated bio-based aggregates such as wood [49], peach shell [1], oil palm shell [50], etc. can improve adhesion to mortar because of the decomposition of organic matter. In this study, the 28-day compressive strength of fibre-reinforced ASC in this study varied between 40.2 MPa and 44.7 MPa, which is significantly higher than the requirements of structural LWAC (> 17 MPa) [51]. Therefore, it can be concluded that fibre reinforcement can further improve the mechanical properties of bio-based ASC.

### 3.2.2 Splitting tensile strength

As shown in Table 4, the addition of PP fibre, G fibre and B fibre significantly increased the splitting tensile strength of ASC. When the $V_f$ varied from 0.25 to 0.50%, the splitting tensile strength of ASC reinforced with PP fibre, G fibre and B fibre increased by 7.4–16.4%, 15.8–24.8% and 19.2–29.1%, respectively, compared to ASC without any fibres. Previous studies [52, 53] indicated that the incorporation of fibres had a significant enhancement in the toughness

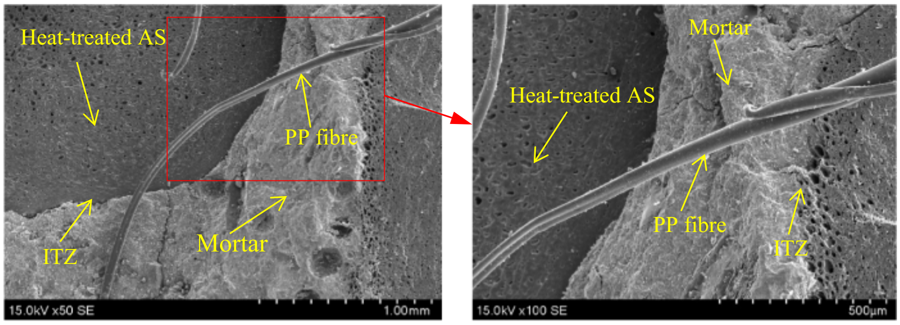


**Fig. 9** Microscope image of concrete containing PP fibre

and the tensile strength due to fibres caused the slowing of crack propagation and thus enhanced mechanical strength and toughness of concrete. However, the splitting tensile strength of ASC decreased as the $V_f$ increased from 0.5 to 0.75%, as shown in Fig. 10. The addition of B fibre contributed to higher tensile properties than PP fibre and G fibre. This may be due to the higher tensile modulus and tensile strength of the B fibre which has more effective fibre bridging capacity for transferring higher tensile stress and improving the crack advanced resistance compared to the PP fibre and G fibre [53].

### 3.2.3 Flexural strength

The effects of fibre volume fraction on flexural strength are presented in Fig. 11. Similar to splitting tensile strength, when the $V_f$ increased from 0.25 to 0.50%, the flexural strength of ASC reinforced with PP fibre, G fibre and B fibre enhanced the flexural strength up to 5.1–14.7%, 12.7–26.5% and 16.3–29.2%, respectively, compared to ASC without any fibres. The flexural strength of ASC decreased as the $V_f$ increased from 0.5 to 0.75%. The schematic diagram of fibre bridging effect is shown in Fig. 12. When the ASC without any fibres was subjected to tension, cracks directly penetrated through the concrete matrix and concrete was severely damaged, which was considered as brittle failure [54]. Moreover, most of the AS aggregate on either side of the crack was broken under the tensile stress due to the low strength of the AS. However, when the fibre was added to the concrete, the failure mode changed from brittle failure to ductile failure due to the redistribution of load-bearing capacity and the fibre arrests cracks [16, 19]. Firstly, the transverse crack developed under increasing tensile stress. When the crack approached a fibre, the stress was transferred by interfacial shear, and then

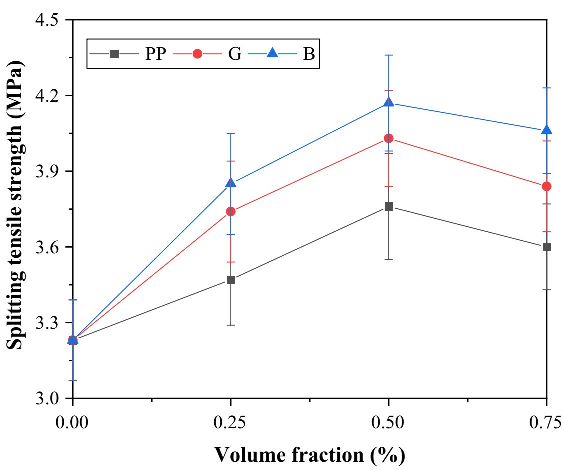


**Fig. 10** Effects of fibre volume fraction on splitting tensile strength

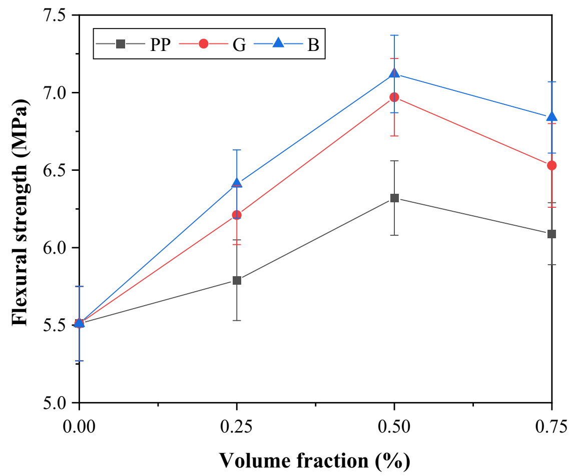


**Fig. 11** Effects of fibre volume fraction on flexural strength

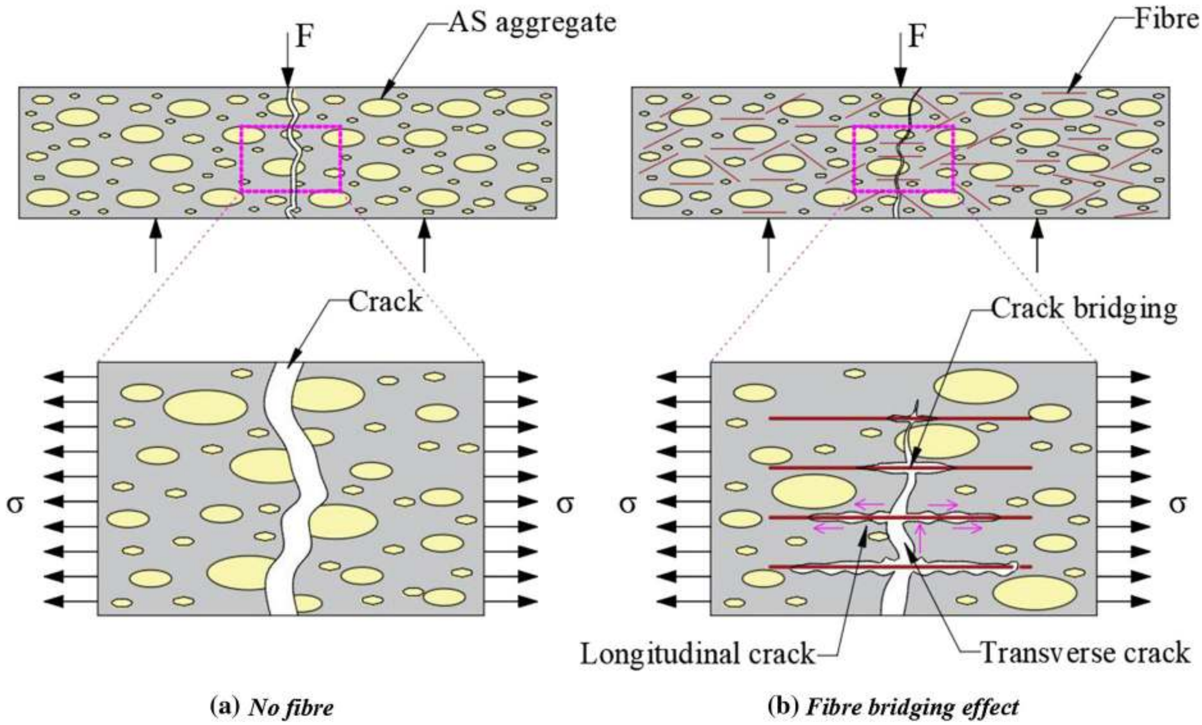


**Fig. 12** Schematic diagram of fibre bridging effect

the crack developed along the longitudinal direction of fibre and the debonding occurred at the fibre-matrix interface because of the stress perpendicular to the expected path of the advancing crack [48]. Finally, all tensile stresses were progressively transferred to the fibre [48, 55, 56]. Most of the fibre formed crack-bridging to delay the development of cracks and slow down the failure, and only a few of the fibre was pulled out after the interfacial shear stress excesses the ultimate bond strength [16, 52]. The crack-bridging of fibre not only improves the load-carrying capacity but also hinders the propagation of post-peak cracks and increases the post-failure toughness of concrete [54]. Besides, using too little fibre to reinforce concrete, causing them to be easily pulled out under ultimate loading, and an optimized amount of fibre should be considered. Therefore, B fibre of 0.5% is suitable for the improvement of the tensile strength of ASC in this study.

### 3.2.4 *Modulus of elasticity*

The modulus of elasticity (E) of ASC is also presented in Table 4. The E of all fibre-reinforced ASC varied between 14.3 GPa and 16.3 GPa, which was in the range of 10–24 GPa for LWAC specified by the CEB/FIP [57]. The addition of fibres improved the E of ASC because the fibre arrests the initial development of the crack and reduces the stress concentration in the crack section under compression loading [19]. The effects of fibre volume fraction on the modulus of elasticity are presented in Fig. 13. As the fibre content increased, the E of ASC first increased and then decreased. When the $V_f$ was 0.5%, ASC reinforced with PP fibre, G fibre and B fibre obtained the highest E, which was increased by 11.6%, 16.7% and 18.1%, respectively, compared to the concrete without any fibres.

## 3.3 Resistance to magnesium sulfate attack

### 3.3.1 *Mass loss*

Sulfate attack is one of the expansion deterioration processes of concrete caused by the reaction of sulfate ions with hydration products of concrete and magnesium attack destroys the C–S–H phase [58]. The mass loss of concrete exposed to magnesium sulfate ($MgSO_4$) solution for 6 months is shown in Fig. 14,

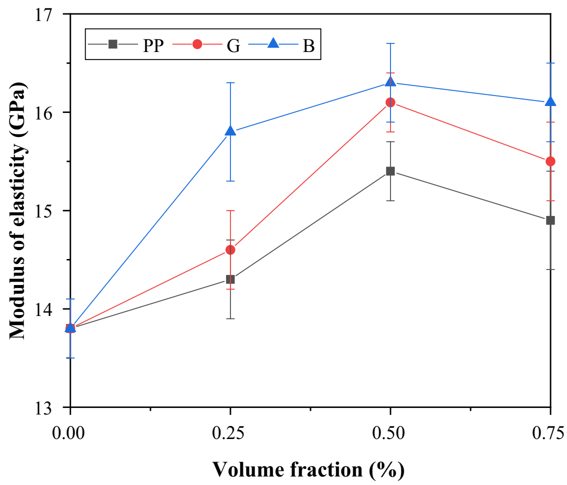


**Fig. 13** Effects of fibre volume fraction on the modulus of elasticity

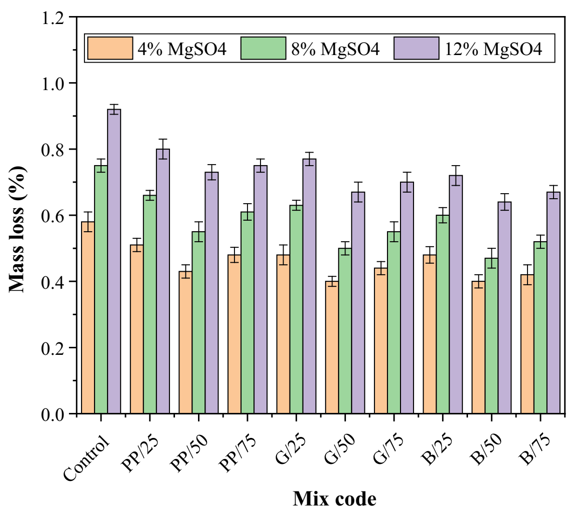


**Fig. 14** Mass loss of ASC exposed to the $MgSO_4$ solution for 6 months

indicating that all concretes exposed to the $MgSO_4$ solution became lighter after 6 months due to the partial damage of the specimen surface caused by the $MgSO_4$ solution [52]. Moreover, higher concentrations of the $MgSO_4$ solution caused more deterioration of specimens due to a significant increase in expansion [59]. The addition of fibres slightly reduced the mass loss of ASC. When ASC exposed to 12% $MgSO_4$ solution for 6 months, the mass loss of ASC containing 0.25–0.75% PP fibre, 0.25–0.75% G fibre and 0.25–0.75% B fibre were 0.73–0.8%, 0.67–0.77% and 0.64–0.72%, which was reduced by 13.0–20.7%, 16.3–27.2% and 21.7–30.4%, respectively, compared to ASC without any fibres.

Microcracks are the main channels where harmful chemical ions such as chloride ions and sulfate ions enter the interior of concrete. As shown in Fig. 15, there are no significant differences in the mechanism of sulfate attack between normal concrete and fibre-reinforced concrete, where mainly the formation of gypsum and ettringite, are causing concrete damage by expansion stress [60]. However, the permeability of concrete is slightly reduced because of the microcrack bridging of the fibre. Besides, the fibre arrests the microcracks caused by expensive stress. As a result, fibre reinforced concrete had less mass loss than concrete without any fibres.

### *3.3.2 Compressive strength loss*

Generally, the mechanical properties of concrete decrease as the immersion time increases due to physical damage or irreversible chemical degradation of composition [53]. As shown in Fig. 16, the addition of fibres enhanced the resistance to magnesium sulfate attack and the ASC exhibited the highest resistance against sulfate attack when the $V_f$ was 0.5%. A higher concentration of $MgSO_4$ solution (12%) had a more negative effect on ASC compared to the low concentration of $MgSO_4$ solution (4%). When the $V_f$ varied from 0.25 to 0.75%, the compressive strength loss of ASC containing PP fibre, G fibre and B fibre exposed to 12% $MgSO_4$ solution for 6 months were 19.8–24%, 18.3–23.4% and 18.0–22.9%, which is a reduction by 14.9–29.8%, 17.0–35.1% and 18.8–36.2%, respectively, compared to ASC without any fibres.

The high permeability increases the path of sulfate ions into the concrete matrix, resulting in the reaction of sulfate ions with calcium hydroxide and alumina-bearing hydration products to produce more gypsum ($CaSO_4 \cdot 2H_2O$) and ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) [59], respectively, which results in cracking and expansion of concrete, according to the following equations [61, 62]:

$$C_4AH_{13} + 3C\bar{S}H_2 + 14H \rightarrow C_6A\bar{S}_3H_{32} + CH \quad (1)$$

$$C_4A\bar{S}H_{12} + 2C\bar{S}H_2 + 16H \rightarrow C_6A\bar{S}_3H_{32} \quad (2)$$

$$C_3A + 3C\bar{S}H_2 + 26H \rightarrow C_6A\bar{S}_3H_{32} \quad (3)$$

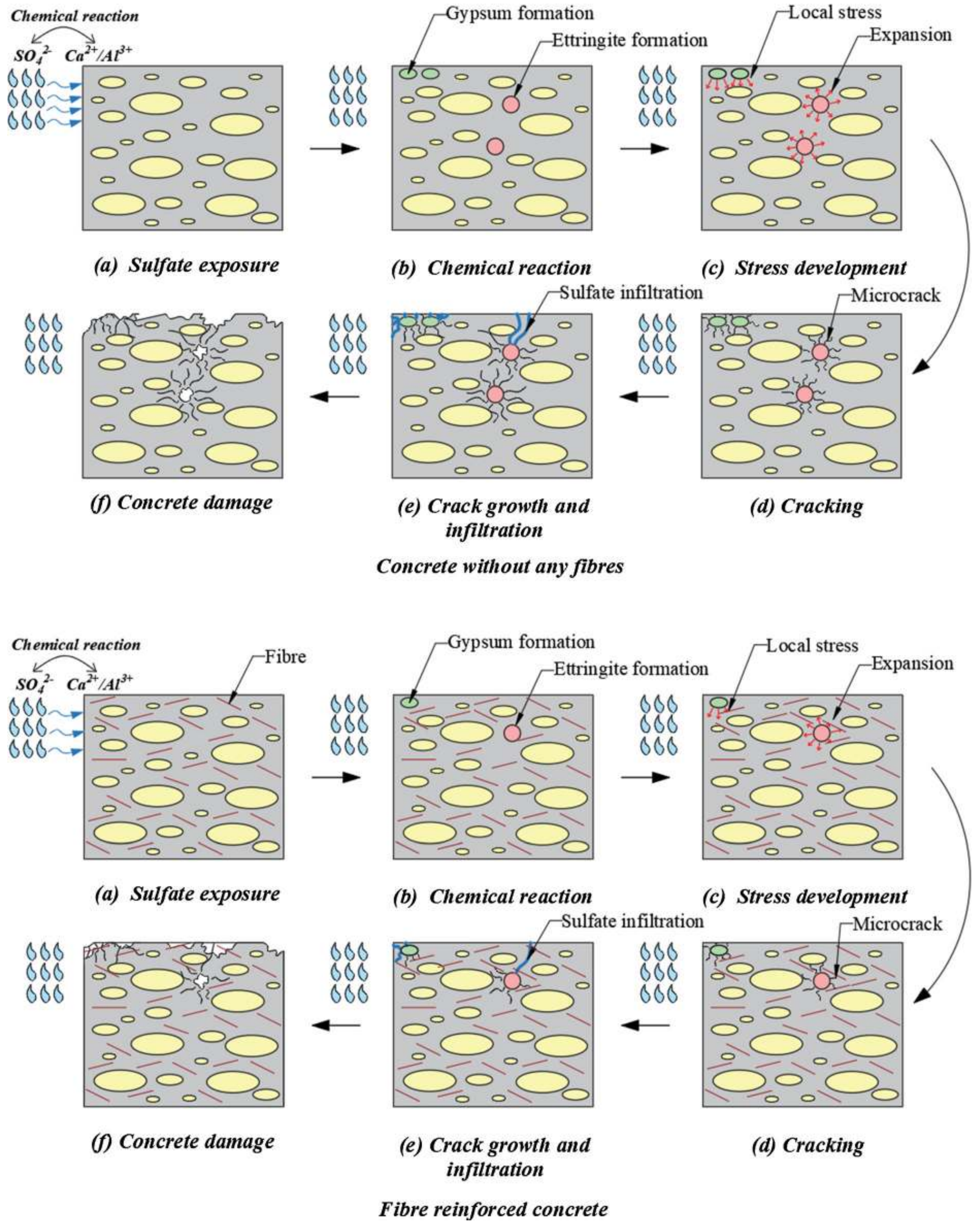


**Fig. 15** Schematic diagram of sulfate attack on concrete

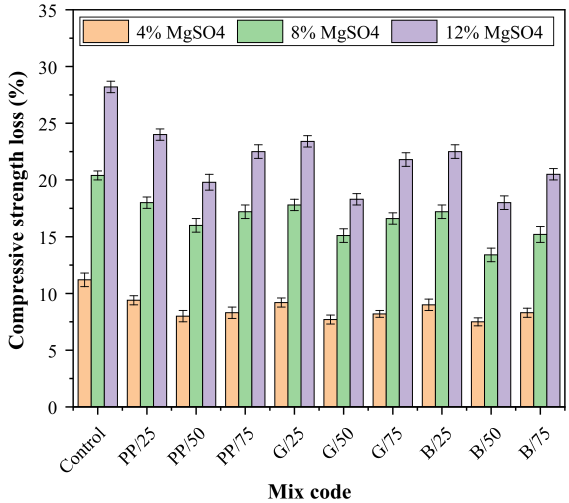


**Fig. 16** Compressive strength loss of ASC exposed to $MgSO_4$ solution for 6 months

where gypsum ($CaSO_4 \cdot 2H_2O$) and ettringite ($3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 32H_2O$) in the equations are referred to $C\bar{S}H_2$ d $C_6A\bar{S}_3H_{32}$, respectively. The others are usual cement chemistry notation: CaO = C, $Al_2O_3$ = A, $SO_3 = \bar{S}$ and $H_2O$ = H.

Because of the low tensile strengtof concrete, the expansive tensile strain from the formation of gypsum and ettringite causes cracking and decreases the mechanical properties [63]. Moreover, the magnesium attack leads to the calcium compounds released from calcium silicate hydrat. (C–S–H), which reduces the stiffness of C–S–H and deterioration of the concrete matrix [64]. Bonen and Cohen [65] reported that a "surface double-layer" of gypsum was formed on the surface of the cement paste matrix by microscopic analysis and only a small amount of ettringite and monosulfate was found.

The loss of strength and adhesion is the main manifestation of magnesium sulfate attack rather than cracking and expansion [57]. The microscope images of PP fibre reinforced ASC exposed to the $MgSO_4$ solution for 6 months are presented in Fig. 17. Clearly, the weak bond at the fibre-mortar interface and aggregate-mortar interface were observed, which resulted in the strength loss of ASC during magnesium sulfate attack. The same phenomenon was reported by Wei et al. [53], when the G fibre reinforced bending sample was immersed in seawater for 90 days, the serious damage at the fibre-matrix interface and some sporadic breaking of fibres was observed during the mechanical test. The PP fibre rupture may be the result of a combination of mechanical damage and magnesium sulfate attack. The type of fibre has a significant effect on chemical attack resistance. Wang et al. [20] observed that the B fibre formed interface was better than that of the G fibre and the flexural modulus of B fibre was very close to the initial value after immersion in an alkaline medium for 90 days. Therefore, the incorporation of the B fibre can significantly reduce the compressive strength loss of ASC and enhance the resistance to magnesium sulfate attack.

## 4 Conclusions

In the present study, heat-treated apricot shell (AS) was utilized as coarse aggregates for producing bio-based lightweight apricot shell concrete (ASC). The effects of polypropylene (PP) fibre, glass (G) fibre and basalt (B) fibre at various volume fractions ($V_f$) (0.25%, 0.5% and 0.75%) on the physical and mechanical properties of ASC were investigated. The resistance to magnesium sulfate attack after 6 months of exposure was evaluated. Based on the obtained results, the following conclusions can be obtained:

1. The fibre type does not significantly affect the physical properties of ASC such as slump, density, water absorption and permeable porosity. However, the slump of ASC decreases with the increase in fibre content. At a fibre content of 0.5%, the ASC obtains the lowest water absorption and permeable porosity.
2. The B fibre has a better improvement in mechanical properties than the PP fibre and G fibre due to the better elastic modulus and tensile strength. When the $V_f$ is 0.5%, the compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of ASC reinforced with B fibre are increased by 16.7%, 29.1%, 29.2%, and 18.1%, respectively, compared to ASC without any fibres.
3. The incorporation of fibres enhances the resistance to magnesium sulfate attack of ASC because the fibre arrests the microcracks caused by the expansive stress. The B fibre can significantly

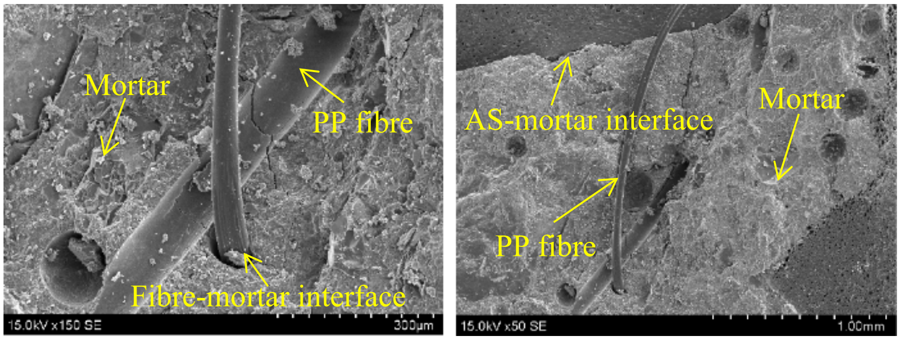


**Fig. 17** Microscope images of PP fibre reinforced ASC after sulfate attack

reduce the mass loss and compressive strength of ASC exposed to a $MgSO_4$ solution for 6 months.

4. The mechanical properties of bio-based ASC and its resistance to magnesium sulfate attack can be significantly improved by incorporating 0.5% B fibre.

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