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REVIEW



Fiber for recycled aggregate concrete reinforcement: a review

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ABSTRACT

Recycled aggregate concrete (RAC) has a significant opposite potential on environmental protection and improvement for its low CO₂ emission during the processing procedure. Performance of RAC may lower than natural aggregate concrete (NAC) mixed from traditional materials, thus various measures are optimized for enhancing the property of RAC to an acceptable level. Researches show that the use of polypropylene (PP) fibers, polyvinyl alcohol (PVA) fibers and basalt fibers (BF) can obviously increase the flexural and split-tensile strength of RAC, and has little effect on the durability of RAC. Some theories are developed by micro-structure analysis on RAC, yet more facts need to be studied and verified in future researches. An important route is to disclose the mechanism of uniform distribution of fibers and nano-materials during RAC mixing and reduce the negative impact of agglomeration of such added materials.

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1. Introduction

With the development of urbanization in China, a quantities of construction and demolition (C&D) waste has been generated, while only about 10% C&D waste (Zhang & Tan, 2020) was reused and recycled. Zheng revealed that around 7.5 billion m³ C&D waste was dumped in China in 2013 (Zheng et al., 2017). At present, the treatment methods of C&D waste include burying and accumulation, which results in the demand for more land resources and seriously disrupts the delicate ecological balance (Shi et al., 2016) since C&D waste can contain harmful substances such as adhesives, lead-based paint, etc. (Education Bureau of Government of Hongkong 2019). In corresponding with such hazardous performance, the definition of recycled aggregate concrete (RAC) was proposed.

Moving beyond the fossil fuel era to a sustainable future requires high-performance recycled materials with low carbon emissions. RAC made from crushed C&D waste has attracted widespread attention. The development and utilization of RAC can not only consume C&D waste, but also reduce resource consumption due to urbanization and environmental pollution caused by mining natural rocks. Notably, the researchers found that the performance of RAC slightly lower than that of natural aggregate concrete (NAC). Some reasons are analyzed, such as the weak interface transition zone (ITZ) (Sidorova et al., 2014), the destruction of recycled aggregate (RA) during processing, and the higher water absorption and porosity of RAC due to the attachment of old mortar. Specially, it is demonstrated that there were two kinds ITZ in RAC, the old ITZ between natural aggregate (NA) and the old mortar, the new ITZ between RA and the new mortar as shown in

Figure 1. These ITZs limit the mechanical strength of RAC, leading to great restrictions on their application.

Creative methods are developed to enhance the performance of RA to meet the needs of RAC and numerous studies on RAC have been reported in the past period of time. In general, these treatment methods can be divided into three categories. (1) Decreasing the porosity of RA, such as accelerated carbonation, biodeposition, the addition of pozzolana or nanoparticles, etc. (2) Property enhancement without RA modification, such as the addition of fiber reinforcement (3) Reduction of adhered mortar, such as acid treatment and thermal treatment. Zheng et al. (2017) reported that the strength of RAC increases up to 15% after CO₂ treatment, while the durability of RAC evaluated in terms of carbonation decreased slightly in comparison with original RAC. Oppositely, the shrinkage and creep of the treated RAC are measurably improved. Obviously, these treatments do not conform to current environmental protection concepts (carbon neutrality) due to a large amount of greenhouse gas emissions. Saravanakumar et al. (2016) pre-soaked RA in HCl and H₂SO₄ solutions after acid treatment. It can be found that the compressive strength of RAC after acid treatment was higher than that of RAC significantly, but lower than that of NAC. Nevertheless, the introduction of chloride ion and sulfate ion will lead to the destruction of concrete. Wang et al. (2017) found out that RA soaked in 3% acetic acid at room temperature for 12h could improve 25% the compressive strength of the RAC in maximum at 28 days. Furthermore, the acidic waste liquid can be used as an admixture to further enhance RAC. Yonggui et al. (2020) found that the composite addition of nano-silica (NS) and basalt fibers (BF) will improve the ITZ performance and elevate temperature performance of the RAC, which could be

attributed to the NS reacting with C-H crystals and accelerating the forming of C-S-H gel. Moreover, the addition of BF improves the mechanical properties of RAC.

Using of fiber with high modulus, excellent toughness, retrievable attribute, e.g. coir fiber (Zhang et al., 2021b; Gupta & Kumar, 2019), jute fiber (Bheel et al., 2021; Zhang et al., 2020), flax fiber (Zhang et al., 2021a), is also a sustainable and effective measure for improving the RAC performance.

However, natural plant fibers are difficult to maintain their original morphology and properties in alkaline concrete pore environment. By contrast, man-made fibers with high modulus, stability, and modifiability have attracted more attention in fiber-reinforced concrete. In this review, we focused on the application of polypropylene (PP) fibers, polyvinyl alcohol (PVA) fibers, and BF in RAC, and the surface morphology of the fiber-reinforced concrete as the Figure 2 showed (Wang et al., 2021).

These fibers act as 'surgical sutures' in concrete to prevent cracks from forming and spreading as the Figure 3 shows (Das et al., 2018). The strengthening mechanism of fiber reinforced concrete can be explained: (1) the composite

material theory. (2) The fiber spacing theory. The strength of fiber, which can be ensured by the type, content, and orientation of fibers, must be higher than the composite cracking stress to prevent crack opening. The composite material theory can be described as the superposition of strength and elastic modulus of fiber and concrete. This theory is based on the fact that fibers are uniformly distributed and isotropic in concrete and there is no relative slip between fibers and mortar. However, to get the result of the enhancement function, the dynamic elastic modulus of fiber must be higher than the mortar. By the aforementioned theory, the boundary effect of the fibers prevents the hardening slurry from being continuous, thus preventing the development of cracks. The more the fiber is added, the more obvious the reinforcement effect will be observed. However, excessive fiber is easy to cause agglomeration, leading to the decrease of workability and performance of concrete. As for the fiber spacing theory, its premise is the uniform distribution of fibers. It is considered that the incorporation of fiber could effectively decrease the diffusion of cracks in concrete.

Despite the fact that there are widely achievement of fiber-reinforced concrete reported, the lack of research on fiber-reinforced RAC is obviously. In this review, we have summarized recent advances in fibers on the performances of RAC.

2. Mechanical properties of RAC with fibers

2.1. Compressive strength

In general, the strength of RAC is inversely proportional to the content of RA due to the RA contains a larger ITZ than NA. Das et al., (2018). examined the difference of compressive strength between RAC and NAC doped with different

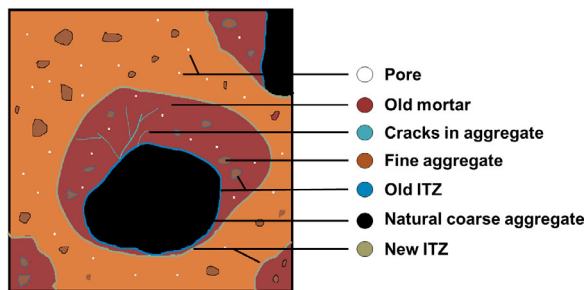


Figure 1. Two ITZs in RAC.

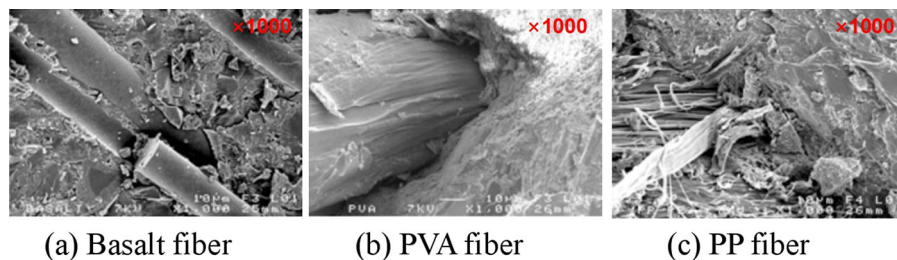


Figure 2. SEM image of fiber-reinforced concrete.

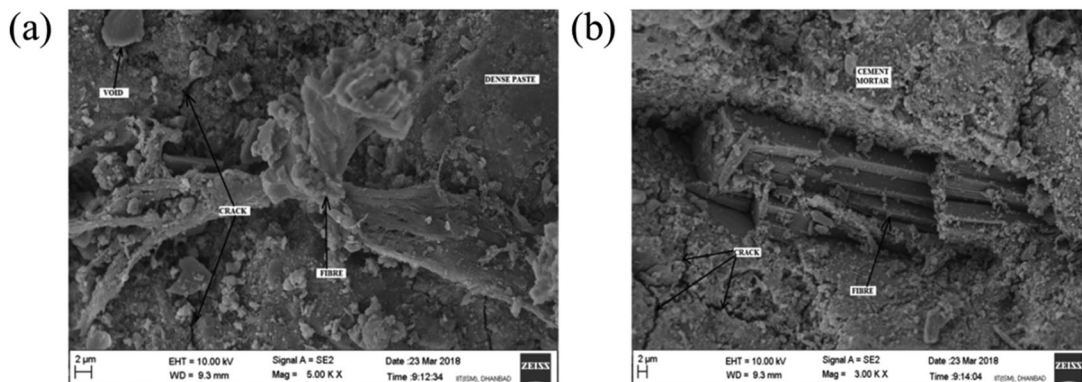


Figure 3. FESEM images of fibers in RAC.

volume fractions of PP fibers. The experimental results revealed that the effect of PP fibers on the compressive strength of concrete can be ignored. The compressive strength of RAC and NAC reached its maximum value when PP fibers content reaches 0.5%, and decreased with further increased of PP fiber content. Under the action of pressure load, concrete will form micro cracks from its original defects and develop into macro cracks, in the concrete mixed with fiber, on the one hand, the fiber across the crack can make the crack expansion delay, thus improving the compressive strength of concrete. On the other hand, the addition of fiber will introduce more original defects (such as ITZs, bubbles, etc.) into the concrete. At the same time, fiber will also increase the yield stress and viscosity of cement mortar in fresh concrete, which will cause the slump of fresh concrete to decrease (Akeed et al., 2022). Therefore, when the fiber volume exceeds a certain threshold, it will be more difficult for the fiber to evenly distribute in the concrete, or even to form a group or ball, which will undoubtedly form more and larger original defects in the concrete, resulting in poor compressive ability of concrete. Huang et al. (2021) found that the compressive strength of RAC reached its maximum value when the content of BF was 0.5%, and when the content of RA increases, the compressive strength of RAC decreased first and then increased again. Interestingly, a convolution neural network was used to predict the compressive strength of BF reinforced RAC which provided a feasible way for further study of fiber reinforced concrete. Wang and Zhu (2021) researched the influence of NS on the mechanical properties of RAC. They found that the addition of NS (0–3%) could improve the compressive strength of RAC, and the compressive strength was further improved after adding PVA fibers. It could be interpreted as follows: at the nano-scale, the micro-pores and micro-cracks in RAC were filled by NS, and at the micron-scale, PVA fibers changed the contact range between mortar and RA, which makes the micro-structure of RAC more compact, as the Figure 4 shows. However, due to the unique size effect of nanomaterials, NS is difficult to disperse in concrete as an additive. Despite the fact that researchers (Quercia et al., 2014; Olivier et al., 2018; Mukharjee & Barai, 2014) have studied many modification methods to reduce the agglomeration of NS, it is difficult to apply them to practical engineering due to its high price.

2.2. Flexural strength

Ismail et al. (2017) demonstrated that remaining mortar on RA provides a weak interface, which lead to a negative effect on the flexural strength of RAC. Singh et al. (2019) studied that PP fibers enhanced the flexural strength of RAC due to the bridging effect. In general, the flexural strength of RAC is proportional to the incorporation of PP fibers. For example, Alyousef et al. (2021) found that the flexural strength of RAC enhanced 20.11% when the matrix contained 0.5% PP fibers (by volume), while this value increased to 28.16% when the PP fibers content increased to 0.75%. This growing trend was also reported by Ahmed and

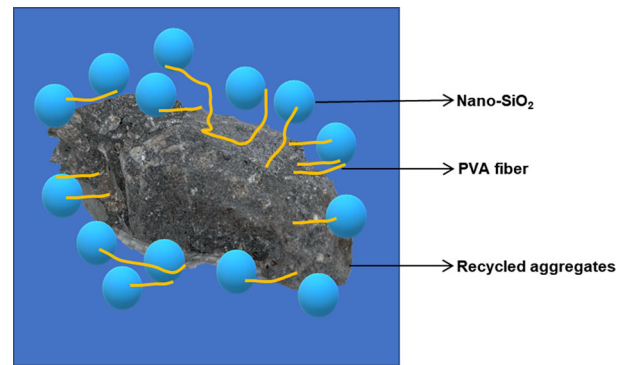


Figure 4. Synergistic mechanism of PVA fiber and Nano-SiO₂.

Lim (2021). They found a flexural strength increment from 4.61% to 11.28% with an increase in the content of PP fibers from 0.15% to 0.6%. However, some researchers (Das et al., 2018; Akça et al., 2015) have found that it has no significant effect on the flexural strength of RAC when the volume fraction of PP fiber exceeds 0.75%. This conclusion provides good guidance for the application of PP fibers in RAC. The BF can also increase the flexural loading capacity of RAC under flexural loading. Katkhuda and Shatarat (2017) studied the improvement of flexural strength of RAC by mixing BF with contents of 0.1%, 0.3%, 0.5%, 1%, and 1.5% (by volume). Their study showed that the optimal BF content to obtain the same flexural strength as NAC was 0.3%, while the flexural strength of RAC was improved by 82.65% when the BF content was 1.5%. Similarly, Alnahhal and Aljidda (2018) also discovered that the flexural strength of RAC made with 25%, 50%, and 100% RA increase by 9.7–37.6%, 5.9–36.3%, and 17.0–41.7% while different BF contents are adopted. Detailed data is shown in Figure 5.

2.3. Splitting tensile strength

The influence of volume fractions of PP fibers and BF on splitting tensile strength of RAC with different content of RA are shown in Figure 6 respectively. Established results have shown that adding appropriate volume fraction of PP fibers and BF could effectively improve the splitting tensile strength of RAC, but the optimal volume content of each fiber obtained by different scholars is different, because of the different water-binder (w/b) ratio of concrete and fibers characteristics (such as length and diameter, etc.). For example, Hanumesh et al. (2018) and Akça et al. (2015) found that when the PP fibers volume fraction was less than 2.0%, the splitting tensile strength of RAC increased gradually with the increase of the PP fibers volume fraction. Ahmed et al. (2020) found that adding 0.6% PP fibers to RAC which contains 50% and 100% RA could increase the splitting strength of the two kinds of concrete by 8.99% and 23.23%, respectively. However, with the volume fraction of PP fibers increases further, the splitting strength of RAC will decrease. Das et al. (2018) also came to similar conclusions. As for BF, Katkhuda and Shatarat (2017) found that the splitting tensile strength of RAC which contains 20% RA displayed an increase of 12.4–40.2% with increasing

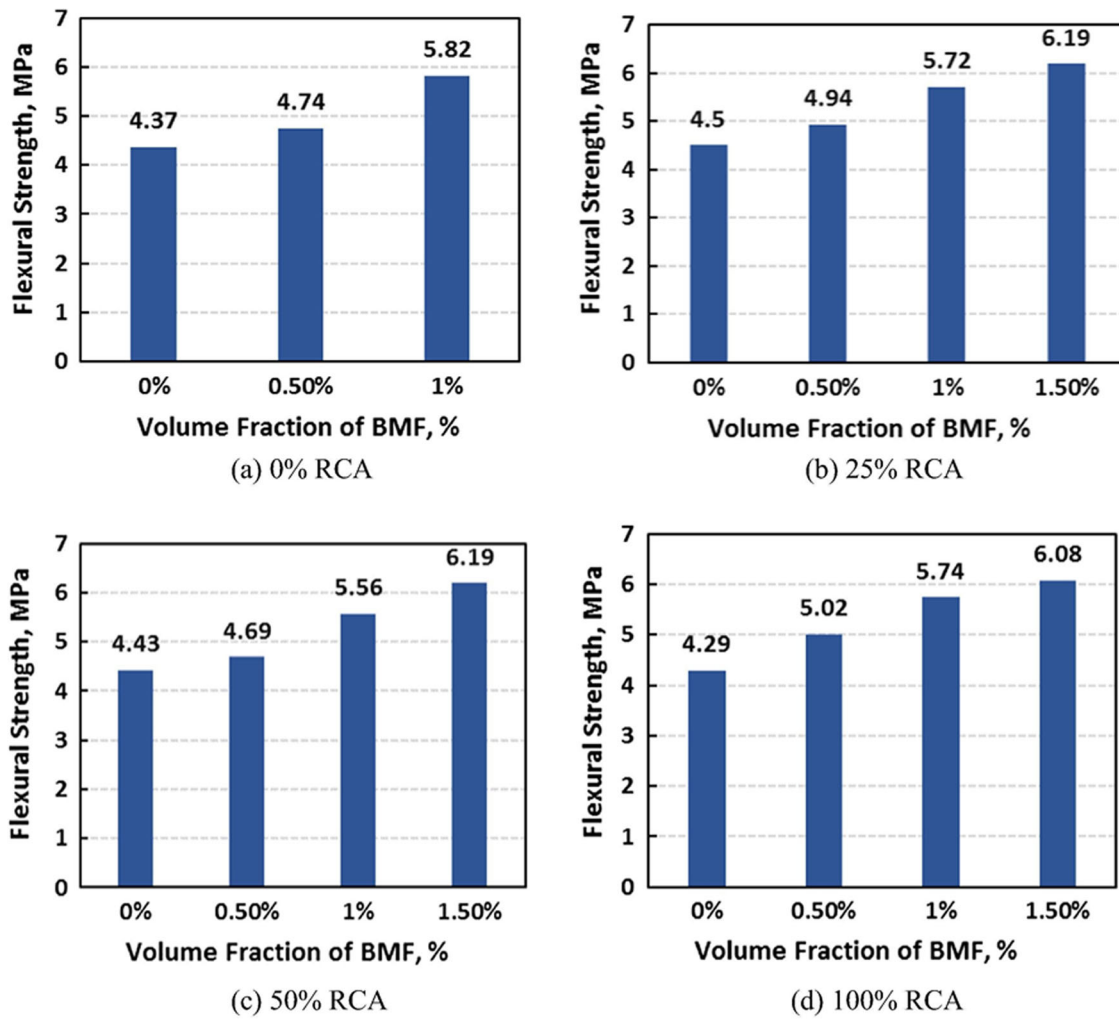


Figure 5. Flexural tensile strength test results for different fiber volume fraction ratios.

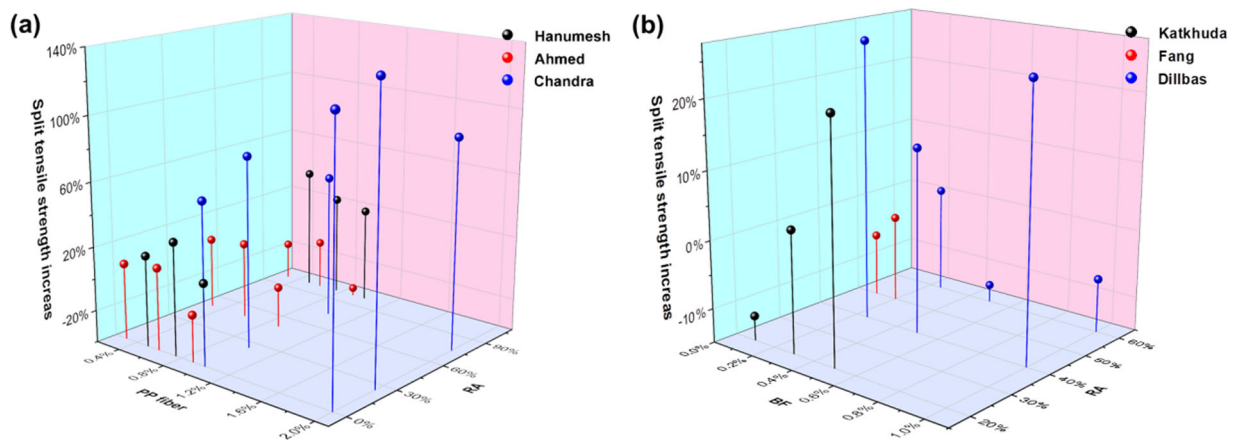


Figure 6. Effect of varying dosages of PP fibers (a) and BF (b) on the flexural strength of RAC.

volume fractions of BF from 0.3% to 1.5%. Furthermore, when the RA was treated with HCl to remove the mortar and impurities on its surface, the splitting strength of RAC could be increased by another 9.0%. Fang et al. (2018) and Dong et al. (2017) found that when the volume fraction of BF was less than 0.2%, the splitting strength of RAC could hardly be improved or even decrease. Adding fibers can improve the splitting tensile strength of concrete mainly due

to its crack-bridging effect (Yu et al., 2018), that is, the fibers across the crack will transfer stress through its bond with the concrete matrix, so as to inhibit the extension of cracks and delay the formation and development of macroscopic cracks, as the Figure 7 shows. When the fiber volume fraction is insufficient, the negative effect of fiber addition (such as introducing more ITZs) on the tensile strength of RAC is greater than its crack-bridging effect, which results

in the decrease of the tensile strength of RAC. However, the excessive fiber can also lead to the decrease of the tensile strength of RAC due to its agglomeration in the concrete.

3. Durability of RAC with fibers

3.1. Chloride penetration resistance

Chloride ion erosion is an important cause of steel corrosion in concrete (Zheng et al., 2021). In particular, the content of chloride ions in surface water and groundwater is particularly high in coastal areas and salt lakes and saline areas. Steel bar is prone to corrosion in this environment (Liu et al., 2021), and the volume expansion generated by corrosion will lead to the expansion and crack damage of cement-based composite materials, which seriously affects the strength and durability of cement-based composite materials, thus posing a threat to the stability and safety of concrete structures. The presence of micro-cracks and voids in RAC increases the permeability of chloride ions, leading to a greater susceptibility to internal corrosion. Ali and Qureshi (2019) found that the internal void structure of RAC is the most important factor affecting chloride ion permeability, far more than material quality and curing condition. As the Figure 8 shows that the values of chloride penetration of RAC containing 50% RA and 100% RA increased by 10% and 39%, respectively, compared to NAC.

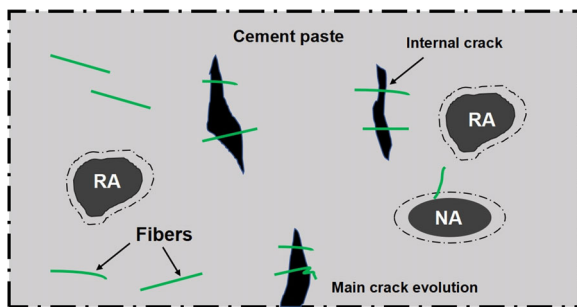


Figure 7. Mechanism of fiber crack-bridging effect.

It is interesting that the addition of glass fibers leads to higher chloride ion permeability, which can be explained by the fact that the glass fiber acts as a channel for chloride ions. They concluded that the small volume of glass fibers and RA had little effect on the chloride permeability of RAC.

3.2. Sulfate resistance

Anhydrous sulfate crystals will absorb water and convert it to sodium sulfate decahydrate (Atahan & Dikme, 2011). During this process, the crystal volume will increase by about three times, resulting in great expansion stress in the concrete interior. Different from the steel corrosion caused by chloride corrosion, sulfate reacts with $\text{Ca}(\text{OH})_2$ to form ettringite (AFT) (Danish & Mosaberpanah, 2022) as the Figure 9 shows. When the concentration of sulfate is higher, gypsum is also produced. In a word, due to the existence of sulfate, the concrete is easy to generate a variety of substances, and the expansion stress in the matrix gradually increases, resulting in the constantly development of initial micro-cracks. Liu et al. (2020). experimentally determined that the dynamic elastic modulus and rupture ratio of concrete were seriously affected by sulfate erosion. The dynamic elastic modulus of concrete increases and then decreases with the increase of sulfate concentration, while the Poisson's ratio of concrete changes in the opposite direction, and both of them eventually reach a stable value. Interestingly, AFT can also be considered a mineral fiber due to its size. Nguyen et al. (2019) developed a high-performance fiber-reinforced recycled concrete from AFT-based binders. They found a combined NaSO_4 - NaCl solution along with numbers of freeze-thaw cycles, PP fibers play an important role in improving durability of concrete. The fiber bridge-effect retarded the diffusion of sulfate and chloride ions into the matrix, and ultimately prevented the expansion caused by corrosive ions in water.

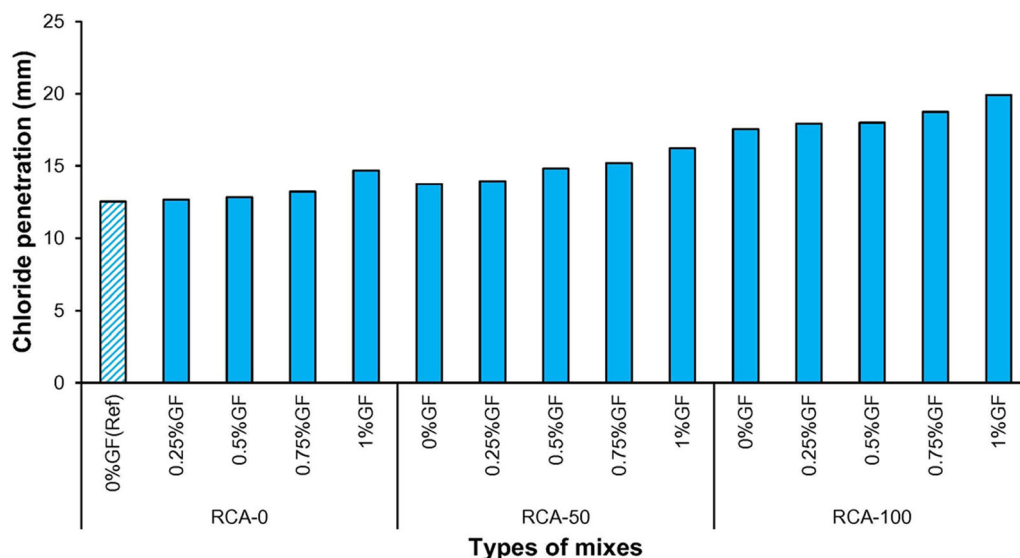


Figure 8. Chloride penetrations in different mixes with varying dosages of glass fiber.

3.3. Freeze-thaw resistance

Freeze-thaw resistance of concrete is regarded as one of the most crucial index to evaluate the durability of concrete, that is determined by measuring the relative dynamic elastic modulus of concrete after numbers of freezing-thawing cycles (Şahin et al., 2021; Hasholt et al., 2019). The structure and distribution of pores (Ren & Lai, 2021) in concrete make credible impact on the freezing-thawing resistance. RAC usually has weak freeze-thaw resistance compared to plain concrete due to the large amount of moisture absorbed by the mortar attached to RA. It can be explained by the fact that water penetrates the concrete and freezes, leading to spalling of mortar and mass loss, further extending the cracks. Therefore, RAC is generally not recommended for use in cold, high-humidity areas due to its weak frost resistance. Šeps et al. (2016) found that PP fibers were not affected by freeze-thaw cycles as the Figure 10 shows.

3.4. Impermeability

The permeability of concrete depends on the void structure inside the concrete. In general, RAC is more vulnerable to permeability than NAC due to RA has more capillary channels. Kamaruzzaman et al. (2016) indicated that the water absorption rate of the specimens with the untreated RCA

was the highest compared to others. From their results, it was found that the water absorption rate of RAC containing 1.5% PP fibers is 72% than that of plain RAC. The improvement can be interpreted as the non-water absorption characteristic of PP fibers, and the changes in the microstructure of hardened mortar caused by proper distribution of fiber.

4. Conclusions and prospect

Recycling and utilization of C&D waste caused by rapid development of economy and society play an important role in sustainable urban development. It is environmentally friendly and economical that using RA from C&D waste to replace NA in the new concrete applications as RAC. Nevertheless, the results showed that RA has negative influences on the mechanical properties and durability of RAC due to its large number of micro-cracks and high water absorption. In this review, we have summarized recent advances in fibers on the performances of RAC. The role of these fibers in concrete is to prevent cracks in RAC from forming and propagation. The 'bridging effect' is a major factor that enhances the mechanical strength of RAC. In general, adding fibers can slightly improve the compressive strength and significantly improve the splitting tensile strength. Moreover, the incorporation of fibers could limit

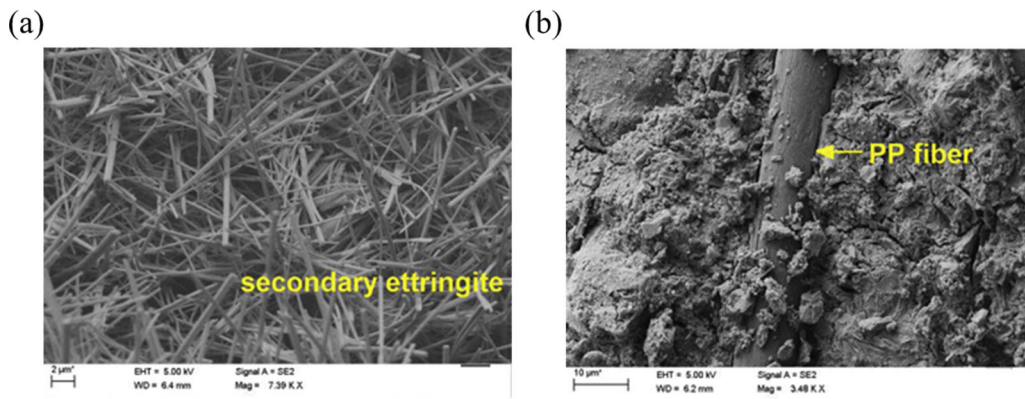


Figure 9. SEM images of ettringite (a) and PP fiber in RAC.

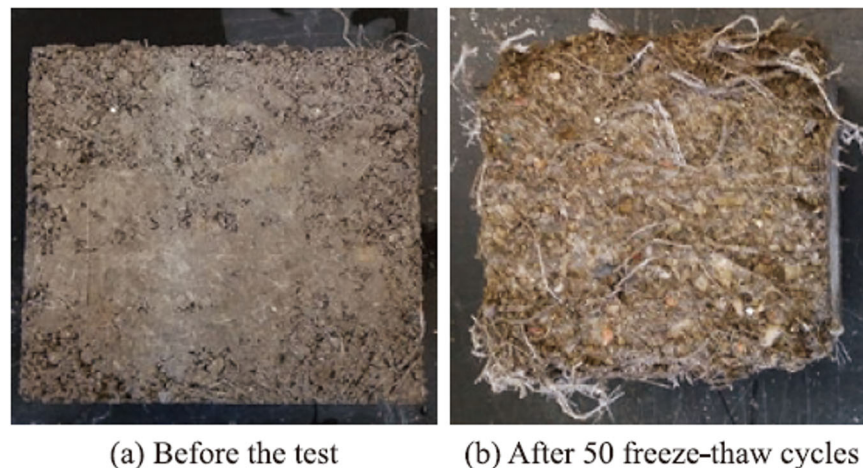


Figure 10. The surface appearances of RAC with fiber.

the detrimental chemicals (e.g. Cl^- , CO_2) and thus the durability of RAC could be improved.

Although fiber-reinforced RAC has achieved great progress in the past period, several goals remain to be achieved. Firstly, more comprehensive studies should be investigated on various types of plant fiber-reinforced RAC, including their macro mechanical properties, durability and micro properties. Besides, the mixed use of multiple fibers and the combined use of other materials will also be the focus of future research. Thirdly, it is well known that the orientation determination of fibers in RAC is the most important factor, and it is necessary to further study the effective technology for uniform distribution of fibers. Lastly, the content, the aspect ratio, and the type of fibers added in the concrete are several important factors that affect RAC. This can be solved by establishing a model to guide the mix design of concrete.

Disclosure statement

The authors declare no conflict of interest.

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