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ORIGINAL ARTICLE

Improving sustainability and compressive strength of fiber reinforced concrete by adding granite powder waste as paste replacement

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Abstract: Fiber reinforced concrete (FRC) typically has large cementitious paste volume and high cementitious content that lead to relatively large carbon footprint and inferior sustainability. Nevertheless, it is envisaged that this problem of FRC may be resolved by adding granite powder waste (GPW) to replace an equal volume of cementitious paste so as to reduce the cement consumption and carbon footprint, recycle the GPW, and thus improve the sustainability. Herein, a series of FRC mixes incorporating polyvinyl alcohol (PVA) fibers and added with GPW to replace part of cementitious paste were produced and tested. The results showed that such paste replacement could reduce the cement consumption by as much as 20%, increase the compressive strength by up to 11%, but decrease the flexural strength by up to 7%. Put together, this could reduce the carbon footprint by as much as 18%, and increase the compressive strength/carbon footprint ratio and flexural strength/carbon footprint ratio by approximately 26% and 19%, respectively. Correlation analysis revealed that the fresh and hardened performances of FRC are highly dependent on its packing density and water film thickness.

Keywords: Carbon footprint, fiber reinforced concrete, granite powder waste, paste replacement, polyvinyl alcohol fiber, waste recycling

1 Introduction

Being the most vastly used construction material globally, concrete has an annual consumption per capita of about 3 tons [1] and an annual consumption worldwide amounting to 25 billion tons [2]. However, this widely utilized and ubiquitous material has two major shortcomings. One is low tensile strength causing high susceptibility to cracking; and the other is inferior sustainability because of its large carbon footprint. The former shortcoming of low tensile strength could cause extensive cracking, leading to serious serviceability and durability problems. On the other hand, the latter shortcoming of large carbon footprint of up to 0.9 ton of CO_2 per ton of cement clinker [3-6] has been causing the generation of a huge amount of CO_2 emission, which accounts for approximately 5 to 7% of the total annual anthropogenic CO_2 emission [7-8].

Aiming to enhance the tensile/flexural performance and crack control of concrete, the incorporation of fibers to transform the concrete to become fiber reinforced concrete (FRC) has been proven to be an effective approach [9-10]. The types of fibers viable for use in FRC include: natural fibers, metallic fibers, mineral fibers, and synthetic fibers [11-13]. Among them, polyvinyl alcohol

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(PVA) fibers, which have both high tensile strength and large ultimate elongation, are highly effective in improving the axial tensile strength, flexural strength, ductility and deformability [14-15]. Particularly, by adding suitable dosages of PVA fibers, the flexural strength of the FRC has been successfully increased by 37% to 116% [12, 16-18]. However, after adding PVA fibers, the concrete mixing would become more difficult and the workability would drop significantly. Consequently, the cementitious paste volume of the FRC would have to be increased, causing the FRC to have generally a relatively high cementitious content and thus a relatively low sustainability.

To enhance the sustainability of a concrete material, lowering the cement content is of cardinal importance. Though the addition of a filler as cement replacement seems to be a straight forward way to cut down the cement consumption, it often impairs the strength because of the corresponding increase in effective water/cementitious, or W/C ratio after adding the filler. For example, it has been reported that the addition of wood waste ash as cement replacement beyond a certain optimum content, which is quite variable depending on the quality of the ash, would decrease the strength [19]. It has also been found that adding limestone fines as cement replacement beyond about 10% would decrease the strength [20]. To lower the cement content without detrimental effect on strength, the filler should be added to replace an equal volume of cementitious paste (cementitious materials + water) without altering the W/C ratio, i.e. as cementitious paste replacement. With no change in W/C ratio, the strength should not be adversely affected. Various types of fillers, such as marble dust, granite dust, limestone fines and ceramic powder, have been successfully applied as cementitious paste replacement to lower the cement content without causing any harmful effect on strength [21-25].

Whilst various types of fillers have been used [26-27], the authors are particularly fond of using a powder waste because this could also help to recycle the waste for minimizing waste disposal. One common type of powder waste is granite powder waste (GPW) generated from stoneware factories during cutting and polishing of granite stoneware. The disposal of GPW deprives valuable landfill space and if not properly dealt with, may lead to pneumoconiosis and silicosis lung disease [28-30]. Therefore, the GPW should better be recycled as a filler to produce concrete. Savadkoohi and Reisi [31], Velumani and Manikandan [32] and Wu et al. [33] have added GPW to replace part of aggregate and thus achieved significant increase in strength and modulus, but such usage of GPW would not directly lower the cement consumption. Singh and Aggarwal [34] have added marble powder waste to partially replace cement and GPW to partially replace aggregate, and found that the addition of 10% marble powder waste content and 25% GPW content would lower the cement consumption by 10% and improve the compressive and flexural strengths, but the addition of more marble powder waste and/or GPW would decrease the compressive and flexural strengths.

However, for FRC, there had been little research on the possible application of the cementitious paste replacement method, which may be more effective than the cement replacement method in reducing the cementitious content and carbon footprint. In the current research, GPW was utilized as cementitious paste replacement to reduce the cementitious paste volume by 0%, 10% or 20% so as to evaluate the effects of such cementitious paste replacement on the compressive and flexural strengths of FRC and more importantly to assess the effectiveness of this replacement method in lowering the carbon footprint of FRC, which tends to be relatively high. A series of FRC mixes incorporating PVA fibers of different lengths and different fiber contents, and with different GPW contents added as cementitious paste replacement have been produced for measuring their compressive and flexural strengths. Moreover, their packing densities, water film thickness (WFT) and paste film thickness (PFT) have been determined to theoretically analyze how these factors affect the workability, compressive strength and flexural strength of FRC and to find out why the replacement of cementitious paste by GPW, which is not cementitious, could significantly increase the compressive strength.

2 Materials

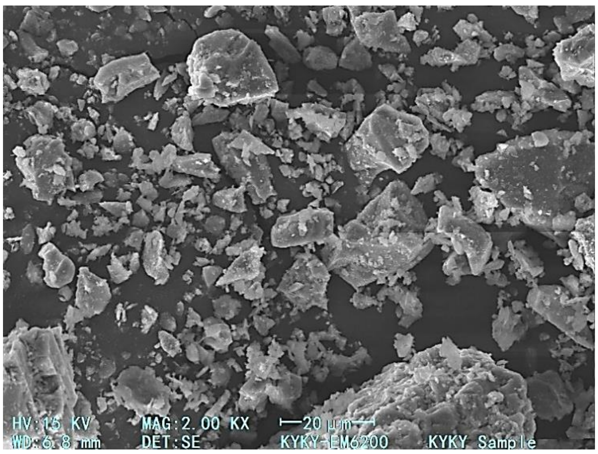
In this study, the constituent materials for producing the FRC comprised cement, GPW, PVA fibers, fine aggregate, coarse aggregate, water, and superplasticizer. The cement was ordinary Portland cement (OPC) of type CEM I class 42.5N complying with BS EN 197: Part 1: 2011 [35]. The GPW was a waste from a granite stoneware factory in Guangdong, China, as depicted in **Fig. 1** [36-38]. **Tab. 1** lists the chemical compositions of the OPC and GPW. Their scanning electronic microscope (SEM) micrographs, depicted in **Fig. 2**, show that both the OPC and GPW particles are angular in shape. The PVA fibers were supplied by Shanghai Yingjia Industrial Development Company Limited. Their physical characteristics, as provided by the supplier, are summarized in **Tab. 2**. The fine and coarse aggregates were crushed granite rock with nominal maximum sizes of respectively 5 mm and 20 mm. Mechanical sieving showed that their gradings met with BS 882: 1992 [39]. The superplasticizer (SP) was polycarboxylate-based and was commonly used for production of high-performance concrete. It is able to disperse the fine particles through both steric hindrance and electrostatic repulsion, thus is particularly effective [40-41].

(a) Cutting of granite panels

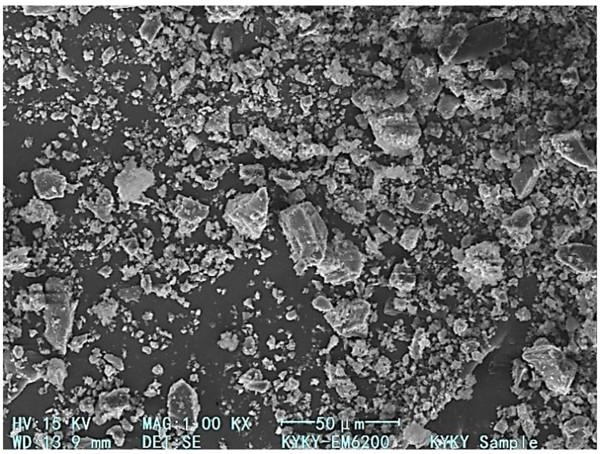
(b) GPW under settling

(c) GPW after oven-drying and smashing

Fig. 1. Photographs showing processing of GPW.



(a) OPC



(b) GPW

Fig. 2. SEM micrographs of OPC and GPW.

Table 1. Chemical compositions of OPC and GPW

Chemical compositions (%)	OPC	GPW
CaO	58.13	2.98
SiO_2	22.92	67.91
Al_2O_3	7.41	13.13
MgO	4.13	0.51
Fe_2O_3	3.68	1.97
TiO_2	0.49	0.36
P_2O_5	0.17	0.38
K_2O	0.16	3.91
Na_2O	0.13	4.69
Loss on ignition at 1000 ℃	2.07	2.91

Table 2. Physical properties of PVA fibers

Properties	Unit	Value
Fiber length	mm	6 or 9
Fiber diameter	μm	31
Relative density	-	1.30
Tensile strength	MPa	1800
Elastic modulus	GPa	37.0
Dry fracture elongation	%	17 ±3.0

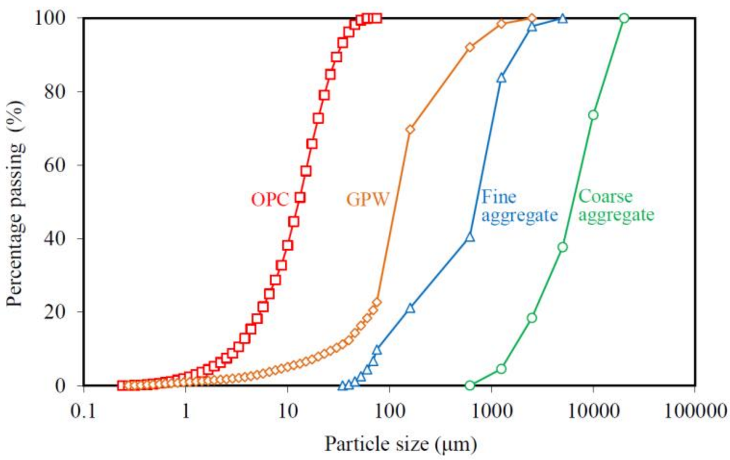


Fig. 3. Particle size distributions of OPC, GPW, fine aggregate and coarse aggregate.

Relative densities of the OPC, GPW, fine aggregate, coarse aggregate, PVA fibers and SP were measured to be respectively 3.13, 2.77, 2.48, 2.60, 1.30 and 1.03. On the other hand, the particle size distributions of the solid constituents, as measured with the mechanical sieving method for the fine aggregate, coarse aggregate and GPW portion coarser than 75 μm, and with the laser diffraction method for the OPC and GPW portion finer than 75 μm, are presented in **Fig. 3**. Based on the measured particle size distributions, the median particle sizes of OPC, GPW, fine aggregate and coarse aggregate are worked out as 12.9 μm, 124 μm, 0.754 mm and 6.72 mm, respectively. Following the procedures to account for the particle angularity [42], their specific surface areas are computed as 1.51×10^6 m^2/m^3, 3.48×10^5 m^2/m^3, 3.52×10^4 m^2/m^3 and 1.17×10^3 m^2/m^3, respectively.

3 Investigation Program

To study the effects of GPW reutilization as paste replacement on the performance and sustainability of FRC, the investigation program consisted of two stages. Stage I was to reveal 'how' the GPW content, fiber length (FL) and fiber content (FC) would affect the workability and strength. The workability of the FRC produced was measured as the SP demand for achieving a certain required slump, and the flexural and compressive strengths were measured by applying four-point bending to prismatic specimens and subsequently applying compression loads to the broken pieces of the prismatic specimens. Then, the carbon footprint, compressive strength/carbon footprint ratio and flexural strength/carbon footprint ratio were calculated to determine the effects on the sustainability. Stage II was to reveal 'why' for all the FRC mixes tested, the GPW added as paste replacement could have the effects revealed in Stage I. For the purpose of revealing 'why', the packing density was measured, and the WFT (water film thickness) and PFT (paste film thickness) were determined to disclose the root causes of the combined effects of the paste replacement, FL and FC.

Overall, 27 concrete mixes were produced for testing. As it is the volume of each constituent material rather than the mass that has a more fundamental role in determining the performance of concrete [43-46], the GPW content, FC, W/C ratio, cementitious paste volume (combined volume of cementitious materials and water) and fine-to-total aggregate ratio were all quantified in volume. The FL was varied between 6 mm and 9 mm, the FC was varied from 0% to 0.8% in increments of 0.2% in terms of volumetric percentage of the concrete mix, and the GPW content was varied from 0% through 10% to 20% as a percentage of the original cementitious paste volume. To focus on the effects of the paste replacement in FRC, the other mix parameters, namely the W/C ratio, original cementitious paste volume, and fine-to-total aggregate ratio, were fixed at 1.2 (equivalent to 0.384 by mass), 0.40, and 0.40, respectively. For each concrete mix, the SP dosage was determined via trial mixing in which the SP was dosed bit-by-bit into the concrete mix until attaining the target slump value of 150 ± 25 mm. To annotate the concrete mixes, they were each assigned a mix no. in the form of F(FL-FC-GPW content) for mixes with fibers or NF(GPW content) for mixes without fibers. The concrete mix proportions are listed in **Tab. 3**. During mixing and testing, the laboratory temperature was regulated to be within 24 ± 2 ℃.

Table 3. Concrete mix proportions

Mix no.: NF(GPW content) or F(FL-FC-GPW content)	Water (kg/m^3)	OPC (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	GPW (kg/m^3)	PVA fiber (kg/m^3)
NF(0)	218.2	568.5	595.2	934.9	0.0	0.0
F(6-0.2-0)	218.2	568.5	593.2	931.8	0.0	2.6
F(6-0.4-0)	218.2	568.5	591.2	928.7	0.0	5.2
F(6-0.6-0)	218.2	568.5	589.2	925.6	0.0	7.8
F(6-0.8-0)	218.2	568.5	587.3	922.5	0.0	10.4
F(9-0.2-0)	218.2	568.5	593.2	931.8	0.0	2.6
F(9-0.4-0)	218.2	568.5	591.2	928.7	0.0	5.2
F(9-0.6-0)	218.2	568.5	589.2	925.6	0.0	7.8
F(9-0.8-0)	218.2	568.5	587.3	922.5	0.0	10.4
NF(10)	196.4	511.7	595.2	934.9	110.9	0.0
F(6-0.2-10)	196.4	511.7	593.2	931.8	110.9	2.6
F(6-0.4-10)	196.4	511.7	591.2	928.7	110.9	5.2
F(6-0.6-10)	196.4	511.7	589.2	925.6	110.9	7.8
F(6-0.8-10)	196.4	511.7	587.3	922.5	110.9	10.4
F(9-0.2-10)	196.4	511.7	593.2	931.8	110.9	2.6
F(9-0.4-10)	196.4	511.7	591.2	928.7	110.9	5.2
F(9-0.6-10)	196.4	511.7	589.2	925.6	110.9	7.8
F(9-0.8-10)	196.4	511.7	587.3	922.5	110.9	10.4
NF(20)	174.5	454.8	595.2	934.9	221.8	0.0
F(6-0.2-20)	174.5	454.8	593.2	931.8	221.8	2.6
F(6-0.4-20)	174.5	454.8	591.2	928.7	221.8	5.2
F(6-0.6-20)	174.5	454.8	589.2	925.6	221.8	7.8
F(6-0.8-20)	174.5	454.8	587.3	922.5	221.8	10.4
F(9-0.2-20)	174.5	454.8	593.2	931.8	221.8	2.6
F(9-0.4-20)	174.5	454.8	591.2	928.7	221.8	5.2
F(9-0.6-20)	174.5	454.8	589.2	925.6	221.8	7.8
F(9-0.8-20)	174.5	454.8	587.3	922.5	221.8	10.4

4 Test Methods

As the test methods are common or standardized, their procedures are only explained in brevity in the following.

4.1 Measurement of SP Demand

The workability was measured through the slump test following BS EN 12350: Part 8: 2019 [47]. The drop in height of the fresh concrete in the slump cone after the slump cone was lifted was taken as the slump result. If any bleeding or segregation was observed, it was recorded as an indication of lack of cohesiveness. For each concrete mix, the SP was dosed bit-by-bit and then the slightly increased slump was measured until the measured slump reaching within 150 ± 25 mm. This would maintain a consistent workability for direct comparison of the performance of concrete mixes produced [24,48].

4.2 Measurement of Strength

The flexural strength was measured in accordance with ASTM C1609/C1609M-19 [49]. For each mix, triplicated 100 × 100 × 400 mm prisms were cast, demoulded at 1-day age and then cured in a water tank controlled at temperature of 20 ± 2 ℃. At 28-day age, the prisms were each tested under flexure in a four-point loading configuration at the third points of the span length to determine the flexural strength. Subsequently, the two broken halves of each prism were collected for compressive strength test as per the procedures stipulated in BS EN 12390: Part 3: 2019 [50]. The measured flexural strengths from the three prisms were averaged to be the flexural strength result whereas the measured compressive strengths from the six broken halves of the three prisms were averaged to be the compressive strength result.

4.3 Quantification of Carbon Footprint

For each concrete mix, its carbon footprint was quantified from the embodied carbon per unit mass of each ingredient and the consumption of each ingredient per unit volume of the concrete. The embodied carbon was according to the representative valuations provided by Hammond and Jones [51], as presented in **Tab. 4**. For the GPW, its embodied carbon is taken as zero because it is a waste from the stoneware industry and if not used would have to be disposed to landfills.

Table 4. Typical values of embodied carbon of ingredients

Ingredient	Embodied carbon (kg CO_2/kg)
Water	0.001
Cement	0.730
Fine aggregate	0.005
Coarse aggregate	0.005
GPW	0.000
PVA fiber	0.450
SP	1.880

4.4 Measurement of Packing Density

The packing density of each solid mixture was determined via the wet packing method [52-53]. To carry out the test, water was added incrementally to the solid mixture so as to form a water-solid mixture. At each water/solid ratio, the solid concentration was computed from the bulk density of the water-solid mixture and the proportion of each solid ingredient. Finally, the highest solid concentration among the water-solid mixtures formed with varying water/solid ratios was taken as the packing density result of this solid mixture. Measurement of the packing density under wet instead of dry condition was to simulate the actual wet condition in the concrete mix where both water and SP are present and to avoid the serious agglomeration of the fine particles in dry condition [54-56].

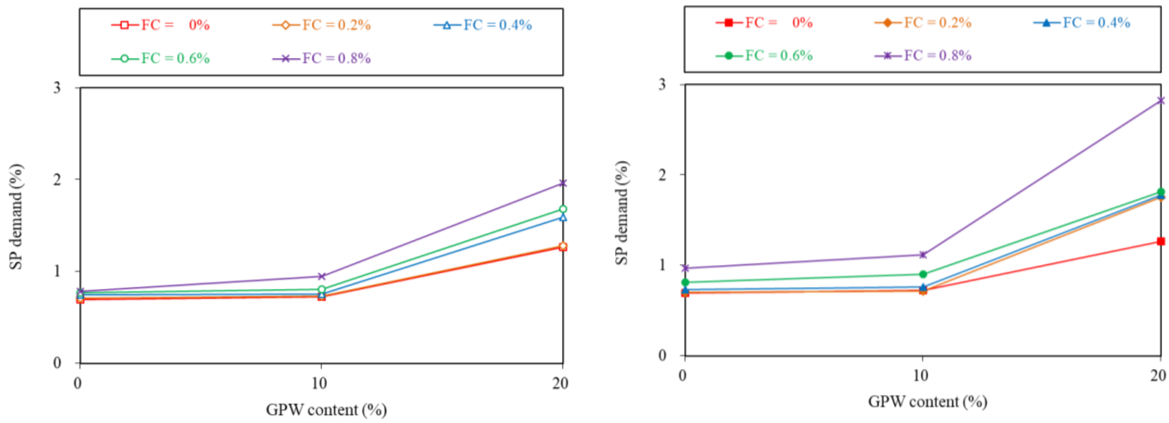
4.5 Determination of Film Thicknesses

The WFT and PFT were determined based on the mix proportions of concrete mix, specific surface area of each solid ingredient, and the measured packing density [43, 57]. As per previous research, the WFT has the physical meaning of being the average thickness of water films coating the surface of all solid particles, while the PFT has the physical meaning of being the average thickness of paste films (the paste includes all fine particles finer than 75 μm which have a tendency to mingle with water and form an inseparable paste) coating the surface of solid particles coarser than 75 μm [58]. The procedures to determine the WFT/PFT are: (1) quantify the voids ratio (voids volume to solid volume ratio) from the packing density; (2) quantify the water ratio and paste ratio from the mix proportions; (3) quantify the excess water ratio and excess paste ratio by deducting the voids ratio from the respective water ratio and paste ratio; (4) quantify the WFT and PFT by dividing the excess water ratio and excess paste ratio by the respective specific surface area.

5 Test Results

5.1 SP Demand

The SP demand results are plotted against the GPW content for various FL and FC in **Fig. 4**. Evidently, the addition of 10% GPW as paste replacement caused little effect on the SP demand when the FC was lower than or equal to 0.4%, but slightly increased the SP demand when the FC was higher. However, the addition of 20% GPW as paste replacement considerably increased the SP demand regardless of the FL and FC. For instance, at FL = 6 mm and FC = 0.4%, the addition of 10% GPW rendered the SP demand nearly unchanged at around 0.76%, while the addition of 20% GPW raised the SP demand from 0.76% to 1.59%. Such observed effects of the GPW on the workability of FRC are similar to those observed by Ling and Kwan [21], who reported that adding limestone fines to replace part of the paste generally lowered the flowability.



(a) FL = 6 mm (b) FL = 9 mm

Fig. 4. SP demand versus GPW content at various FL and FC.

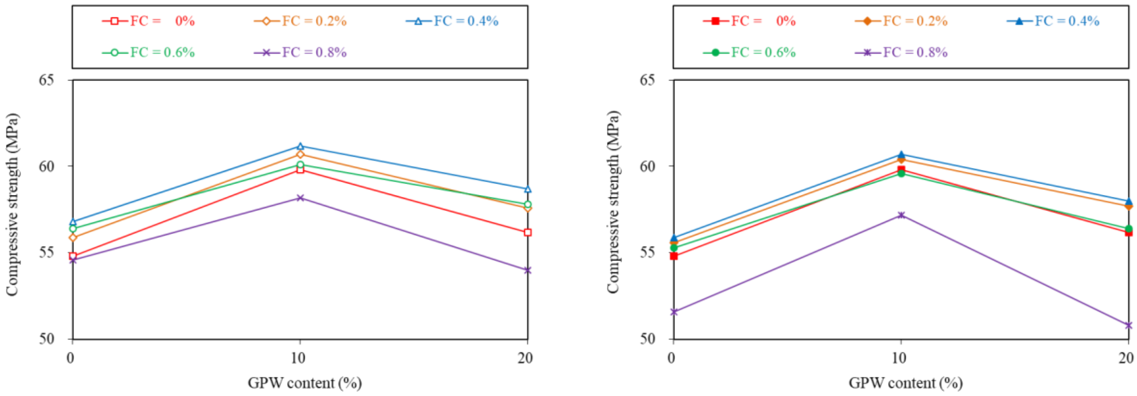
On the other hand, regardless of whether GPW had been added, a higher FC and/or a longer FL always increased the SP demand, especially at a relatively high GPW content. This was because the fibers tended to entangle with each other to hinder the deformation and movement of the FRC mix, and the fiber entanglement was generally more serious at higher FC and/or longer FL. Such observed effects are consistent with those observed by Sun et al. [59], who found that the incorporation of fibers generally decreased the fluidity of FRC. This is the reason why in FRC, there is a tendency to increase the cementitious paste volume to compensate for the significant reduction in workability and flowability due to fibers addition.

Overall, the above results revealed that the workability of the FRC mixes with GPW added to replace up to 20% cementitious paste could be maintained within the target range of 150 ±25 mm slump simply by adjusting the SP dosage upwards. In other words, the loss of workability attributed to reutilization of GPW as paste replacement could be compensated by adding more SP. When conducting the slump tests of the FRC mixes in this study, no bleeding or segregation was ever observed. Hence, in spite of the increase in SP dosage, the FRC mixes incorporating GPW as paste replacement had remained sufficiently cohesive to avoid bleeding and segregation.

5.2 Compressive Strength

The compressive strength results are plotted against the GPW content for various FL and FC in **Fig. 5**. Evidently, regardless of the FL and FC, the addition of 10% GPW remarkably increased the compressive strength, but the addition of 20% GPW turned to decrease the compressive strength compared to that at 10% GPW. For instance, at FL = 6 mm and FC = 0.4%, the addition of 10% GPW increased the compressive strength from 56.8 to 61.2 MPa by 7.7%, while the addition of 20% GPW decreased the compressive strength from 61.2 to 58.7 MPa, which was still 3.3% higher than the compressive strength at 0% GPW. Apparently, an optimum GPW content for maximum compressive strength existed at about 10%. Overall, the addition of 10% GPW could enhance the compressive strength by up to about 11% regardless of the FL and FC, but the addition of 20% GPW could enhance the compressive strength by just about 3% and only under the condition that FC ≤ 0.6%. The above results that paste replacement could increase the compressive strength is aligning with the findings by Chu et al. [60], who showed that the usage of waste glass powder in replacing part of the paste could significantly enhance the compressive strength of ultra-high-performance FRC.

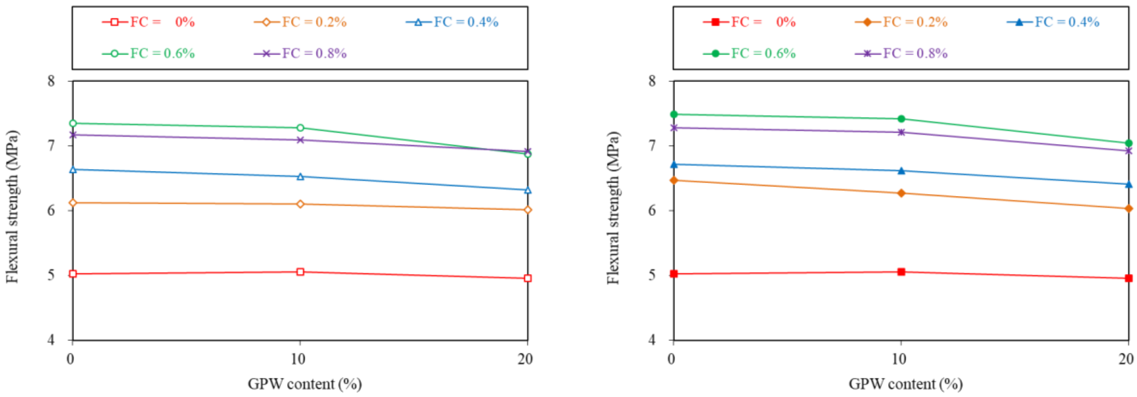
Regarding the effects of fiber addition, the compressive strength first increased as the FC increased from 0 to 0.4%, then turned to decrease as the FC further increased. It is apparent that the optimum FC for maximum compressive strength was about 0.4%. Such observed effects agree quite well with those of Ling et al. [16], who reported that incorporating 0.6% PVA fibers best enhanced the compressive strength. However, the actual increase in compressive strength due to fiber addition was only 3% to 4% and therefore relatively, the increase in compressive strength due to GPW addition is larger.



(a) FL = 6 mm (b) FL = 9 mm

Fig. 5. Compressive strength versus GPW content at various FL and FC.

5.3 Flexural Strength



(a) FL = 6 mm (b) FL = 9 mm

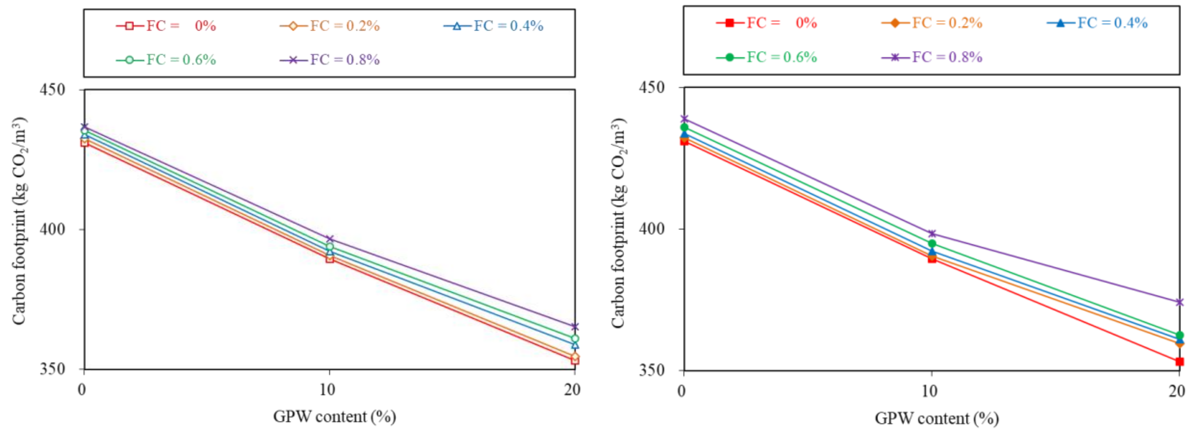
Fig. 6. Flexural strength versus GPW content at various FL and FC.

The flexural strength results are plotted against the GPW content for various FL and FC in **Fig. 6**. Somehow, regardless of the FL and FC, the incorporation of GPW always slightly decreased the flexural strength. For instance, at FL = 6 mm and FC = 0.4%, the addition of 10% GPW decreased the flexural strength by 1.5% and the addition of 20% GPW decreased the flexural strength by 4.7%. At FL = 9 mm and FC = 0.4%, the addition of 10% GPW decreased the flexural strength by 1.5% and the addition of 20% GPW decreased the flexural strength by 4.6%. Nevertheless, such reductions in flexural strength were at the most only about 7%.

Regarding the effects of FC, the flexural strength first increased as the FC increased from 0 to 0.6%, then stopped increasing or turned to decrease marginally when the FC further increased from 0.6% to 0.8%. Apparently, the optimum FC for maximum flexural strength was about 0.6%. Regarding the effects of FL, it is noted that a longer FL of 9 mm, compared to a shorter FL of 6 mm, generally resulted in a slightly higher flexural strength at the same FC. These manifested effects are similar to those observed by Mosavinejad et al. [17].

5.4 Cement Consumption and Carbon Footprint

The adoption of GPW to replace a certain percentage of the cementitious paste would directly reduce the cementitious paste volume and thus also the cement consumption by the same percentage. As cement is the major ingredient contributing to the carbon footprint, the carbon footprint can be significantly reduced as depicted in **Fig. 7**, where the carbon footprint is plotted against the GPW content for various FL and FC. Evidently, regardless of the FL and FC, the incorporation of up to 20% GPW as paste replacement had reduced the carbon footprint by a maximum of about 18%.



(a) FL = 6 mm (b) FL = 9 mm

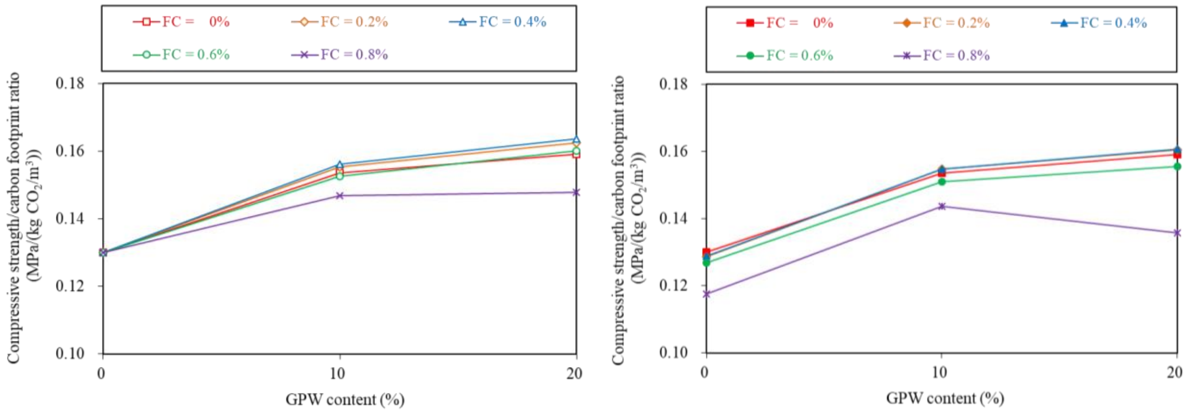
Fig. 7. Carbon footprint versus GPW content at various FL and FC.

On the other hand, the carbon footprint generally became slightly larger as the FC increased because of the embodied carbon of the PVA fibers. Likewise, the carbon footprint also became slightly larger as the FL increased because of the somewhat higher SP demand and the embodied carbon of the increased SP dosage.

5.5 Strength/Carbon Footprint Ratio

Besides reducing the carbon footprint per unit volume of concrete, increasing the strength is also an effective way to enhance the sustainability because with a higher strength, less volume of concrete would be needed to carry the same load and less dead load would need to be carried. Hence, the sustainability of concrete should not be evaluated only on equal volume basis but should more rationally be evaluated on equal strength basis. It is thus advocated that the effect of adding GPW on sustainability of FRC should be assessed in terms of the carbon footprint/strength ratio or the strength/carbon footprint ratio. As a higher strength/carbon footprint ratio indicates a higher sustainability performance, the strength/carbon footprint ratio is adopted herein.

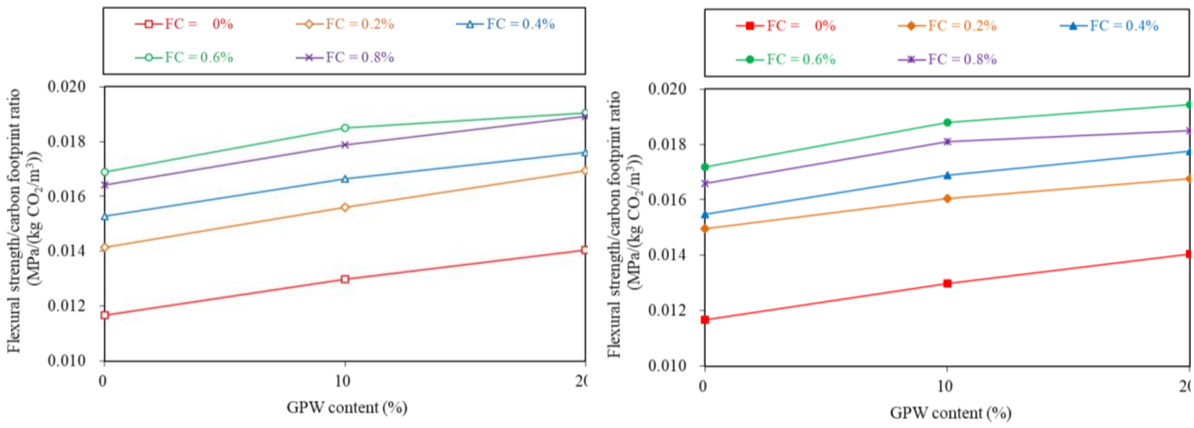
The compressive strength/carbon footprint ratio results are plotted against the GPW content for various FL and FC in **Fig. 8**. These results demonstrated that regardless of the FL and FC, adding GPW as paste replacement up to 20% always increased the compressive strength/carbon footprint ratio. For instance, at FL = 6 mm and FC = 0.4%, the addition of 20% GPW increased the compressive strength/carbon footprint ratio from 0.131 to 0.164 MPa/(kg CO_2/m^3) by 25.2%. This beneficial effect of GPW as paste replacement was due to the simultaneous increase in compressive strength and decrease in carbon footprint. Therefore, the production of FRC with GPW added as paste replacement is able to concurrently enhance the sustainability and compressive strength. This is recommended to be a directive to the production of sustainable FRC for structural applications [61].



(a) FL = 6 mm (b) FL = 9 mm

Fig. 8. Compressive strength/carbon footprint ratio versus GPW content at various FL and FC.

The flexural strength/carbon footprint ratio results are plotted against the GPW content for various FL and FC in **Fig. 9**. These results demonstrated that regardless of the FL and FC, adding GPW as paste replacement up to 20% steadily increased the flexural strength/carbon footprint ratio. For instance, at FL = 6 mm and FC = 0.4%, the addition of 20% GPW increased the flexural strength/carbon footprint ratio from 0.0153 to 0.0176 MPa/(kg CO_2/m^3) by 15.0%. This beneficial effect of GPW as paste replacement was due to the mild decrease in flexural strength being proportionately smaller than the decrease in carbon footprint. Hence, although the adoption of GPW as paste replacement would not increase the flexural strength, it could still increase the flexural strength/carbon footprint ratio by up to about 15%.



(a) FL = 6 mm (b) FL = 9 mm

Fig. 9. Flexural strength/carbon footprint ratio versus GPW content at various FL and FC.

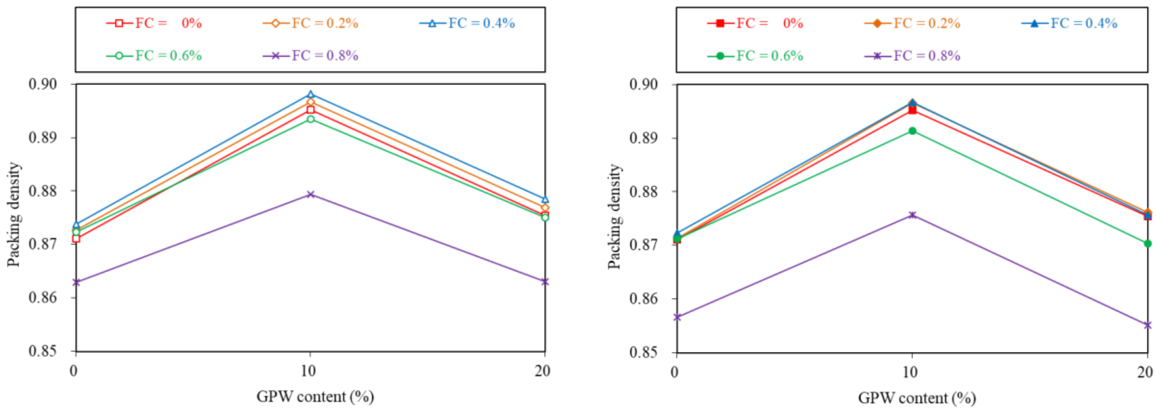
6 Root Causes of the Effects of Paste Replacement

Based on previous findings about the roles of paste volume in the fresh and hardened properties of FRC [62] and also on previous research about the roles of packing density, WFT and PFT in the fresh and hardened properties of other types of concrete [22-25], it is envisaged that the respective changes in paste volume, packing density, WFT and PFT should be the main factors causing the effects of the paste replacement by GPW. To unveil the root causes of the manifested effects of paste replacement by

GPW, the paste volume, packing density and film thicknesses have been quantified and the workability, compressive strength and flexural strength are correlated to these factors by regression analysis.

6.1 Packing Density

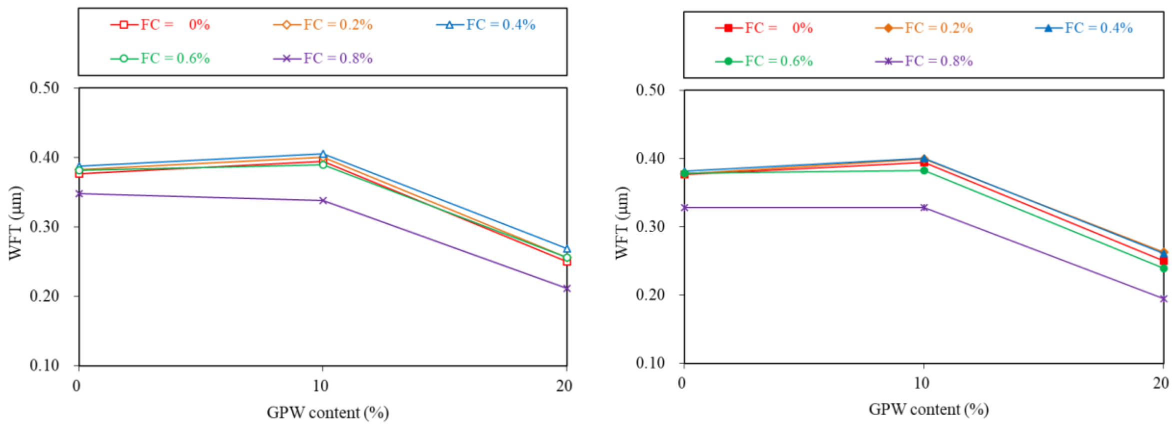
The packing density results are plotted against the GPW content for various FL and FC in **Fig. 10**. These results revealed that regardless of the FL and FC, adding 10% GPW densified the packing, while adding 20% GPW turned to lower the packing density relative to that at 10% GPW. Apparently, an optimum GPW content for densest packing existed at 10%. The increase in packing density with GPW content at low GPW content may be attributed to the filling effect of GPW into the voids between the aggregate particles, whereas the decrease in packing density as the GPW content further increased at high GPW content may be ascribed to the loosening effect of GPW in the voids pushing the larger size aggregate particles apart. On the other hand, the FC had the effects of marginally increasing the packing density when FC ≤ 0.4%, marginally decreasing the packing density when FC > 0.4%, and significantly decreasing the packing density when FC > 0.6%. Moreover, the packing density was somewhat lower at FL = 9 mm than at FL = 6 mm, especially when FC > 0.6%. Hence, overall, when FC > 0.6%, the fibers had certain adverse effect on the packing density.



(a) FL = 6 mm (b) FL = 9 mm

Fig. 10. Packing density versus GPW content at various FL and FC.

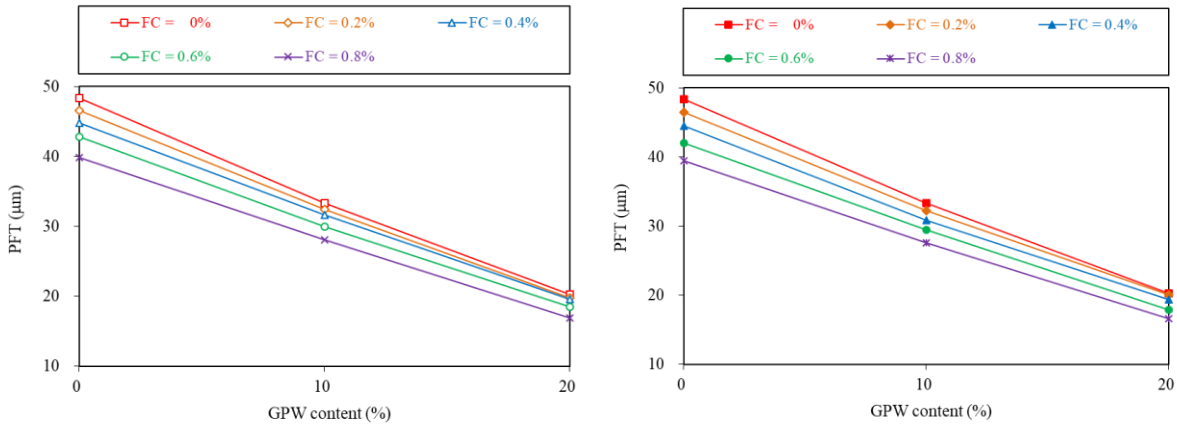
6.2 Film Thicknesses



(a) FL = 6 mm (b) FL = 9 mm

Fig. 11. WFT versus GPW content at various FL and FC.

The WFT and PFT results are plotted against the GPW content for various FL and FC in **Fig. 11** and **Fig. 12**, respectively. From the WFT results, evidently regardless of the FL and FC, the addition of 10% GPW marginally increased the WFT, while the addition of 20% GPW turned to substantially reduce the WFT. Such variation of the WFT with the GPW content was the joint effects of variations in packing density and specific surface area as the GPW content increased. On the other hand, when FC ≤ 0.6%, the effect of the FC content was quite small but when FC > 0.6%, the WFT decreased remarkably as the FC further increased. From the PFT results, evidently regardless of the FL and FC, adding GPW to replace paste up to 20% always substantially reduced the PFT. This was because of the decrease in paste volume and the increase in specific surface area arising from the addition of GPW to replace an equal volume of cementitious paste. Likewise, a higher FC also always reduced the PFT, but the effect was relatively small. This was because when more fibers were added, the total solid surface area to be coated with paste became larger thereby thinning down the PFT. Comparatively, the FL had little effect on the PFT.



(a) FL = 6 mm (b) FL = 9 mm

Fig. 12. PFT versus GPW content at various FL and FC.

6.3 Root Cause behind the Effects on Workability

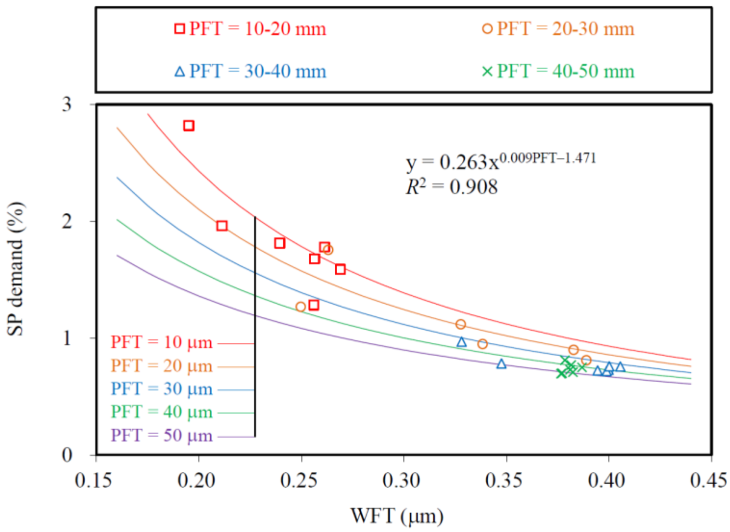


Fig. 13. Correlation of SP demand to WFT and PFT.

To unveil the root cause of the manifested effects of GPW addition as paste replacement and incorporation of PVA fibers on the workability (in terms of SP demand), the SP demand is correlated with the WFT and PFT by regression analysis as depicted in **Fig. 13**. The best-fit equation and the R^2 value obtained from the regression analysis are juxtaposed in the figure for ease of reference. Good correlation with most data points in close proximity to the best-fit curves and a R^2 value of 0.908 has been obtained. The overall trend as reflected by the best-fit curves indicates that the SP demand increases steadily as the WFT and/or PFT decrease. Hence, the root cause behind the effects of GPW and PVA fibers on the SP demand was the corresponding changes in WFT and PFT due to the additions of GPW and PVA fibers. Based on this correlation, it is suggested that to maintain reasonable workability and avoid excessive SP dosage, the WFT and PFT should be designed to be at least 0.20 μm and 15 μm, respectively.

6.4 Root Cause behind the Effects on Compressive Strength

To unveil the root cause of the manifested effects of GPW addition as paste replacement and incorporation of PVA fibers on the compressive strength, the compressive strength is correlated to the packing density by regression analysis as depicted in **Fig. 14**. The best-fit equation and the R^2 value obtained are juxtaposed in the figure. Very good correlation with the data points lying very closely to the best-fit curve and a high R^2 value of 0.955 has been yielded. The overall trend demonstrates that the compressive strength increases steadily with the packing density. Hence, the root cause behind the effects of GPW and PVA fibers on the compressive strength was the respective change in packing density due to the additions of GPW and PVA fibers. A far-reaching implication is that the use of GPW, though not cementitious, could enhance the compressive strength by filling into the voids between the aggregate particles to densify the packing structure.

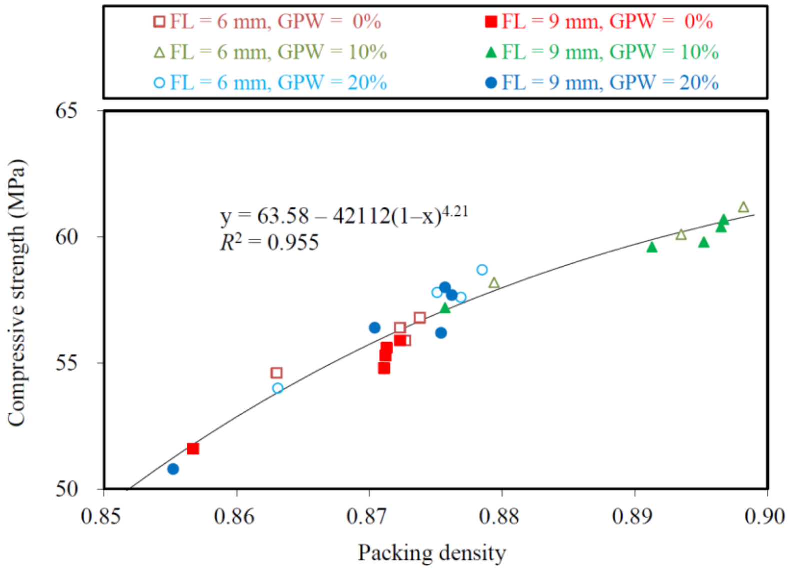
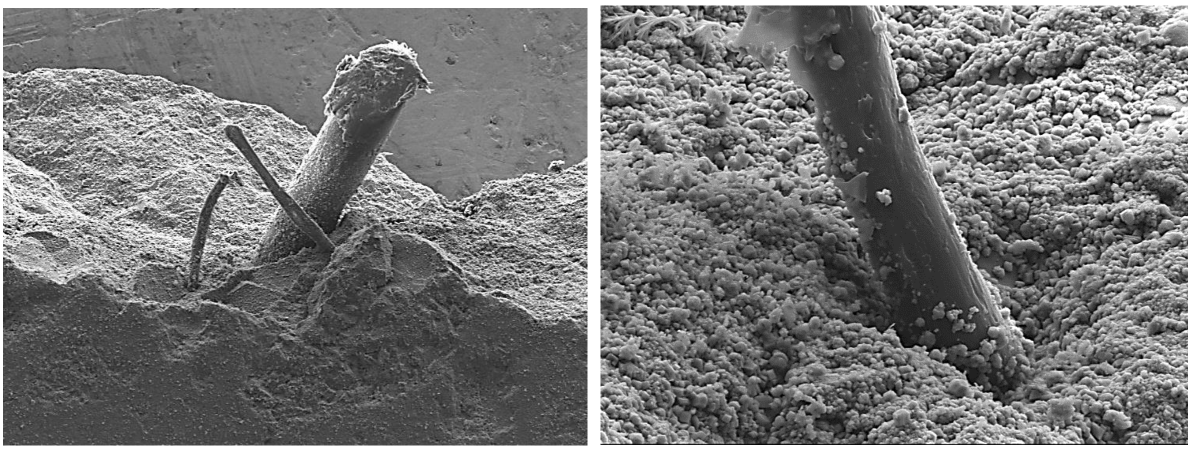


Fig. 14. Correlation of compressive strength to packing density.

6.5 Root Cause behind the Effects on Flexural Strength



(a) 50x magnification (b) 500x magnification

Fig. 15. SEM micrographs showing PVA fiber in hardened paste.

Physically, the fibers in the fresh FRC are embedded inside the paste and when obstructed by solid particles, have to flex themselves to avoid the boundaries of the solid particles. SEM micrographs of the PVA fibers in the hardened FRC have been obtained and shown in **Fig. 15**. These images depict that the flexible PVA fibers were embedded and anchored in the paste. Based on these images, it is conceived that the PVA fibers would generally follow the channels of paste inside the FRC to the effect that when the paste volume is relatively large, the fibers would lay out more freely in the paste but when the paste volume is relatively small, the fibers would lay out themselves in a crooked manner causing them to be less effective in taking up tensile stresses. Hence, it is envisaged that the reduction in paste volume due to GPW addition as paste replacement could adversely affect the effectiveness of the fibers added and thus decrease the flexural strength of the hardened FRC.

To unveil the root cause of the manifested effects of GPW addition as paste replacement and incorporation of PVA fibers on the flexural strength, the flexural strength is correlated with the FC, FL and GPW content by regression analysis as depicted in **Fig. 16**. The best-fit equation and the R^2 value obtained are juxtaposed in the figure. Very good correlation with the data points lying very closely to the best-fit curves and a high R^2 value of 0.964 has been yielded. The overall trend indicates that regardless of the GPW content, the FC remains the major factor governing the flexural strength whereas the FL has only a small positive effect. More importantly, despite the resulting reduction in paste volume, the addition of GPW to replace paste up to 20% would only slightly decrease the flexural strength by a few percent.

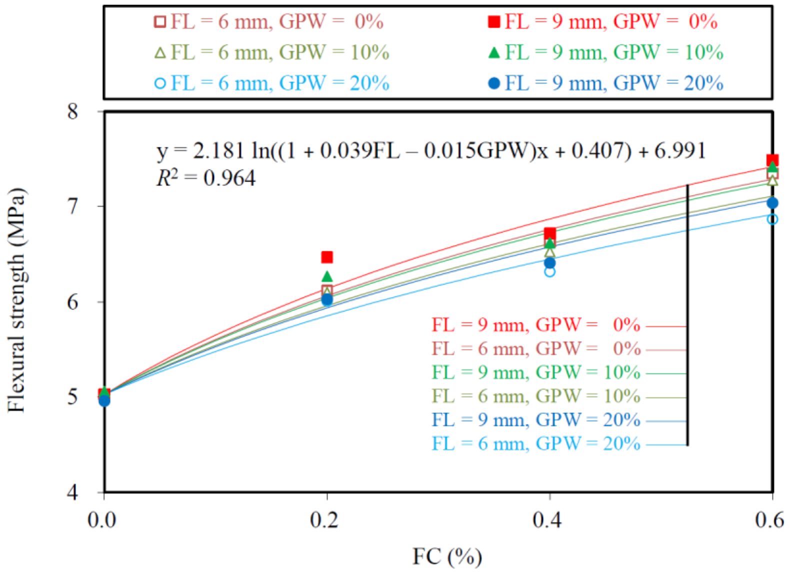


Fig. 16. Correlation of flexural strength to FL, FC and GPW content.

7 Conclusions

This study has explored and heralded the possibility of reutilizing granite powder waste (GPW) as paste replacement in fiber reinforced concrete (FRC) made with polyvinyl alcohol (PVA) fibers to reduce waste disposal, cement consumption and carbon footprint, and if possible, to improve performance via packing density optimization. A total of 27 FRC mixes with various GPW content, fiber length (FL) and fiber content (FC) were tested. And, to unveil the root causes behind the effects of the GPW and PVA fibers on the workability, compressive strength and flexural strength, the packing density, water film thickness (WFT) and paste film thickness (PFT) were determined. The major findings of the study are hereunder summarized:

(1) The adoption of 10% GPW did not change significantly the superplasticizer (SP) demand when FC $\leq$ 0.4% but slightly increased the SP demand at higher FC, while the adoption of 20% GPW always significantly increased the SP demand.

(2) The adoption of up to 20% GPW effectively decreased the cement consumption by up to 20% and the carbon footprint by up to 18%. However, the incorporation of PVA fibers slightly increased the carbon footprint.

(3) The adoption of 10% GPW enhanced the compressive strength by up to 11%, while the

adoption of 20% GPW turned to reduce the compressive strength relative to that at 10% GPW. However, the addition of PVA fibers had only a small effect on the compressive strength.

(4) The adoption of up to 20% GPW reduced the flexural strength by up to 7%. However, the addition of up to 0.6% PVA fiber substantially increased the flexural strength, especially when longer fibers with FL = 9 mm were used.

(5) The adoption of up to 20% GPW improved the compressive strength/carbon footprint ratio by up to 26%.

(6) The adoption of up to 20% GPW improved the flexural strength/carbon footprint ratio by up to 15%.

(7) The key factors controlling the workability are the WFT and PFT. To maintain reasonable workability and avoid excessive SP dosage, it is advisable to design the WFT and PFT to be at least 0.20 µm and 15 µm, respectively.

(8) The governing factor affecting the compressive strength is the packing density, which is maximum at about 10% GPW content. Hence, for achieving highest compressive strength, the packing density should be optimized.

(9) The governing factor affecting the flexural strength is the FC. Due to the reduction in paste volume, the adoption of GPW also has certain effect. But even the adoption of up to 20% GPW would only slightly decrease the flexural strength.

Overall, the reutilization of GPW as paste replacement in FRC would significantly increase the compressive strength, slightly decrease the flexural strength, and substantially enhance the sustainability of FRC as represented by the improvements in compressive strength/carbon footprint ratio and flexural strength/carbon footprint ratio.

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CRediT authorship contribution statement

P.L. Ng: Investigation, Formal analysis, Funding acquisition, Writing – original draft. **J.J. Chen**: Conceptualization, Funding acquisition, Investigation, Writing – original draft. **A.K.H. Kwan**: Formal analysis, Supervision, Writing – review & editing. **G.X. Guan**: Investigation, Supervision.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

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