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Impact energy absorption and mechanical properties of fibre reinforced cementitious composite containing crumb rubber

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ABSTRACT: Fibre reinforced cementitious composites (FRCC) are known for their superior material properties, including high tensile strength and ductility, which make them attractive for structural applications. However, to further enhance their toughness properties and impact energy absorption (IEA), FRCC containing crumb rubber (CR) was investigated to mitigate cracking and brittleness under impact loads. Two CR sizes, 0.5–2 mm and 2–5 mm, replaced 5%, 10%, and 15% of fine aggregate, while PVA fibre dosage varied at 1%, 1.5%, and 2%. In FRCC mixes, the addition of CR reduced density, compressive strength, and flexural strength. However, incorporating 10% CR (5 mm) increased the toughness index by 30% compared to the control specimen, while 15% CR (5 mm) with 2% PVA fibre enhanced IEA by approximately 12%. The statistical results of the two-way ANOVA test indicated that both PVA fibre and CR content significantly influenced the enhancement of IEA in FRCC.

KEY WORDS: Fibre reinforced cementitious composite; Impact energy absorption; Toughness index; Mechanical properties; Crumb rubber; Statistical analysis.

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RESUMEN: *Absorción de energía de impacto y propiedades mecánicas de compuestos cementiceos reforzados con fibra que contiene caucho granulado*. Los compuestos cementíceos reforzados con fibra (FRCC) son conocidos por sus propiedades superiores, incluida su alta resistencia a la tracción y ductilidad, lo que los hace atractivos para aplicaciones estructurales. Para mejorar las propiedades de tenacidad y absorción de energía de impacto (IEA), se investigó el FRCC con caucho granulado (CR) para mitigar la aparición de fisuras y la fragilidad bajo cargas de impacto. Dos tamaños de CR, 0,5–2 mm y 2–5 mm, reemplazaron el 5%, 10% y 15% delárido fino, mientras que la fibra de PVA varió entre 1%, 1,5% y 2%. La adición de CR redujo la densidad, la resistencia a la compresión y a la flexión. Sin embargo, un 10% de CR (5 mm) aumentó el índice de tenacidad en un 30%, y un 15% de CR (5 mm) con 2% de fibra de PVA mejoró la IEA en un 12%. La prueba ANOVA de dos vías indicó que el contenido de fibra de PVA y CR influyeron significativamente en la IEA del FRCC.

PALABRAS CLAVE: Compuesto cementíceo reforzado con fibras; Absorción de energía de impacto; Índice de dureza; Propiedades mecánicas; Caucho granulado; Análisis estadístico.

1. INTRODUCTION

The fibre reinforced cementitious composite (FRCC) is a renowned mortar-based composite that has superior material properties compared to ordinary concrete, such as high tensile strength and greatly improved ductility, which makes it appealing for use. In the context of enhancing the materials properties of FRCC, previous studies (1, 2) have reported that crumb rubber (CR) is one of the potential materials to add to FRCC since incorporating CR in mixes may enhance the toughness and impact energy absorption (IEA) of cementitious composites.

To further highlight the importance of CR from waste tyres, it's worth noting that the United States produced a total of 9.2 million tonnes of waste comprising rubber and leather materials. Within this waste stream, only 1.7 million tonnes were determined to be eligible for recycling, denoting their potential to be processed into reusable materials (3). Furthermore, every year, the improper disposal of over 500 million used tyres in landfills without any additional utilization presents multiple dangers to both society and the environment (1). The illegal dumping and open burning of worn tyre waste have seriously threatened public health in releasing pollutants into the surrounding soil, groundwater, and rivers. In response to environmental and public health problems, deploying the circular economy practices by recycling worn tyres to optimize waste usage would be beneficial.

The CR is produced in specific manufacturers by special mills that crush the tyre rubber particles to smaller sizes ranging from 0.425 – 4.75 mm (2). Over the past 20 years, there has been a lot of interest in the use of CR particles as an alternative aggregate in concrete. Incorporating CR in FRCC materials enhances sustainability by reducing the need for natural resources of aggregates, improving energy absorption, and promoting waste utilization (4, 5). CR also has inherent energy-absorbing properties, which can enhance the impact resistance of FRCC materials, making structures more resilient to dynamic loads (such as impact) and stresses (6). Additionally, research findings show that the energy absorption capacity was higher in waste tyre rubber aggregate concrete mixtures containing 5% and 10% rubber compared to the control concrete mixture (7).

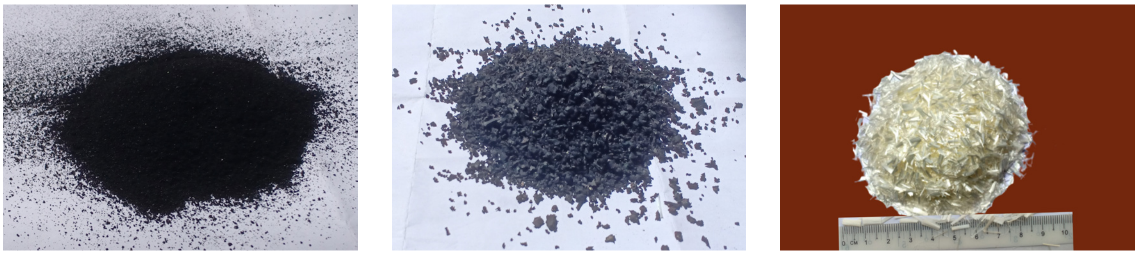
Additionally, the incorporation of polyvinyl alcohol (PVA) fibre in cementitious composite mixes has a remarkable impact, notably by increasing tensile stress and strain capacities while enhancing toughness (8, 9), thus reducing stress concentrations on internal defects (10). This improvement leads to enhanced bending resistance (11). The excellent bonding between the cementitious matrix with PVA fibre has demonstrated its ability to improve mechanical properties, impact resistance, and fracture toughness in both FRCC and engineered cementitious composite (ECC) (2, 3, 7, 12). Furthermore, previous studies (13) have reported that the IEA of structures under impact load is crucial, especially in scenarios like seismic events or other dynamic loads where unexpected failures can occur. In line with these findings, researchers (14) have investigated the impact resistance of fibre reinforced mortar under dynamic loading conditions using the Charpy impact test to understand their performance as impact energy increases with increasing fibre content.

In FRCC materials, particularly containing CR, which may offer higher tensile strength and ductility compared to standard concrete, further study is needed on the IEA capacity under dynamic loads (impact loads) (15, 16), which serves as one of the motivations for this study. Therefore, this study investigates the IEA of FRCC incorporating different sizes of CR through the utilization of the Charpy impact test method. The CR content was varied at fine aggregate replacement percentages of 0%, 5%, 10%, and 15% in the FRCC. Comprehensive testing was performed to evaluate the workability, density, compressive strength, flexural strength, toughness index, and IEA of the FRCC specimens. In this context, the study statically evaluates the variability and reliability of PVA fibre and CR content in improving the IEA of FRCC materials. Finally, this research aims to evaluate the optimum mechanical properties resulting from the combination of PVA fibre and CR in cementitious composites, along with enhancing IEA of FRCC. The novelty of the research lies in the enhancement of IEA under impact loads achieved by incorporating CR into FRCC, a goal pursued through dedicated experimental investigation and statistical analysis. Statistical analysis played a crucial role in this study due to the combination of numerous materials in the FRCC mixture and the highly variable results observed in IEA.

2. EXPERIMENTAL PROGRAM

2.1. Materials

In this study, ordinary Portland cement (OPC) Type I obtained from Tasek Corporation Berhad, which complies with the standard ASTM C150/C150M-22, and ground granulated blast furnace slag (GGBS), which meets the standard ASTM C989/C989M-11, were used as binders in the composite mixes. Fine silica sand with a maximum size of 0.5 mm, specific gravity of 2.61, fineness modulus of 2.2, and unit weight of 1600 kg/m³ was used as a fine aggregate. Two sizes of CR were utilized as partial sand replacements in the mixes with a specific gravity of 1.14. The sizes used were 0.5 mm to 2 mm (termed as size '2') and 2 mm to 5 mm (termed as size '5'). The physical appearance of the CR is presented in Figure 1. Polyvinyl alcohol (PVA) fibre (Figure 1c) with 8 mm length, aspect ratio of 210 and tensile strength of 1600 MPa (17) was added in all mixes. To improve the workability and flowability of the mixtures, superplasticizer (SP) Sika® ViscoCrete®-2044 was used as a high-range water reducer, which complies with the standard EN 934-2.



(a) (a) (c)

Figure 1. General appearance of CR; (a) 0.5-2mm (b) 2-5mm and (c) Physical appearance of PVA fibre.

2.2.1. Mixture proportion

A total of 21 mixtures were prepared in this study, where the GGBS to OPC ratio was maintained at 1.6, and a water-binder (W/B) ratio of 0.25 was adopted. The variables are the CR content in different sizes and contents, as well as the fibre dosages. The percentages of CR used were 5%, 10%, and 15% by volume to replace sand. Additionally, SP was added by 0.4%, 0.5%, and 0.6% of binder materials for mixes containing 1%, 1.5%, and 2% PVA fibre, respectively. The mixture proportion used in this study was based on previous studies conducted on FRCC (18, 19) and ECC (20, 21) mixes.

Table 1 outlines the mix proportions of the cementitious composite utilized in this study, with the mixtures categorized as follows: "PVA 1.0 CTR" designates control specimens that utilized 1% of PVA fibre in the cementitious composite. "PVA 1.0 CR 5-2" denotes the incorporation of 5% CR with maximum size of 2 mm (0.5 – 2 mm) as replacement for fine aggregate, along with the addition of 1% PVA fibre in the composite. Similarly, "PVA 1.0 CR 5-5" designates the inclusion of 5% CR with maximum size of 5 mm (2 – 5 mm) as replacement for fine aggregate, as well as the addition of 1% PVA fibre in the composite.

Table 1. Materials mix proportion (in kg/m³) and slump (in mm).

Mix Designation	Cement	GGBS	Sand	CR	Water	SP	PVA	Slump
PVA 1.0 CTR	555	887	447	-	361	5.8	14.4	168
PVA 1.0 CR 5-2	555	887	424	9.8	361	5.8	14.4	165
PVA 1.0 CR 10-2	555	887	402	19.7	361	5.8	14.4	165
PVA 1.0 CR 15-2	555	887	340	29.5	361	5.8	14.4	165
PVA 1.0 CR 5-5	555	887	424	9.8	361	5.8	14.4	166
PVA 1.0 CR 10-5	555	887	402	19.7	361	5.8	14.4	165
PVA 1.0 CR 15-5	555	887	380	29.5	361	5.8	14.4	166
PVA 1.5 CTR	555	887	447	-	361	7.2	21.6	172
PVA 1.5 CR 5-2	555	887	424	9.8	361	7.2	21.6	170
PVA 1.5 CR 10-2	555	887	402	19.7	361	7.2	21.6	168
PVA 1.5 CR 15-2	555	887	380	29.5	361	7.2	21.6	170
PVA 1.5 CR 5-5	555	887	424	9.8	361	7.2	21.6	175
PVA 1.5 CR 10-5	555	887	402	19.7	361	7.2	21.6	172
PVA 1.5 CR 15-5	555	887	380	29.5	361	7.2	21.6	170
PVA 2.0 CTR	555	887	447	-	361	8.6	28.8	168
PVA 2.0 CR 5-2	555	887	424	9.8	361	8.6	28.8	172
PVA 2.0 CR 10-2	555	887	402	19.7	361	8.6	28.8	170
PVA 2.0 CR 15-2	555	887	380	29.5	361	8.6	28.8	170
PVA 2.0 CR 5-5	555	887	424	9.8	361	8.6	28.8	168
PVA 2.0 CR 10-5	555	887	402	19.7	361	8.6	28.8	170
PVA 2.0 CR 15-5	555	887	380	29.5	361	8.6	28.8	165

2.2.2. Specimen preparation

The SPAR Table Top Mixer SP-800 - 8 Litres was utilized for mixing. The mixing process was initiated by introducing the dry materials, including sand and CR, into the mixing bowl for a duration of 60 seconds. This was followed by adding cement and GGBS into the mixing bowl for an additional 60 seconds. The SP and 80% of the required water were pre-mixed, and then slowly added to the mixing bowl over a period of 60 seconds. The mixture was then stopped and run at medium speed for a duration of 120 seconds. Next, the PVA fibre was introduced into the mixture, along with the remaining water, and mixed for 60 seconds. The mixture was again stopped and run at medium speed for a duration of 180 seconds (22). Once the cementitious composite was homogeneously mixed, it was poured into pre-oiled moulds and vibrated in two layers. The vibration duration was 15 s for each layer using an electric vibrating table, totalling 30 s for the two layers of specimen casting. The moulds were then covered with polythene and left in laboratory conditions at 75 ± 5% humidity and 28 ± 2 °C temperature for 24 hours. After demoulding, the specimens were cured in water for 28 days before being tested, and the water temperature was 24 °C in the storage tank (23).

2.3. Test methods

2.3.1. Workability

The present study utilized the flow table test to evaluate the workability of the fresh cementitious mixture. The procedure adhered to ASTM C230 (24), which stipulates a flow range of 170 mm ± 10 mm (23).

2.3.2. Compressive strength

The compressive strength analysis was carried out on specimens with dimensions of 50 mm × 50 mm × 50 mm in accordance with ASTM C109 (25) using an automatic compression machine with a 2000 kN capacity. The tests were performed under load control with an increasing load rate of 900 N/S. A total of 3 specimens were evaluated for each mixture to obtain the average compressive strength at the ages of 28 days, respectively.

2.3.3. Flexural behaviour

The study utilized 3 prismatic specimens (160 mm × 40 mm × 40 mm) for each mixture, which were cured for 28 days. The flexural strength of the specimens was determined by subjecting them to a three-point bending test at a constant loading rate of 0.25 mm/min using an INSTRON Universal Testing Machine with a load capacity of 100 kN.

The toughness index (TI) is an important parameter used to evaluate the fracture behaviour of FRCC containing CR (FRCC-CR). The TI of FRCC-CR mixes refer to the energy absorbed by the material during fracture. It is a measure of the composite's ability to resist crack propagation and deform plastically before failure. Plastic deformation in this case causes the specimen to first crack and then bend, eventually increasing toughness until it breaks under the flexural load. Higher TI indicates that the FRCC has better fracture resistance and can withstand higher levels of stress before failure. The failure of the specimen can be determined by observing the initial crack, followed by a gradual increase in flexural load until failure (maximum load), which is confirmed by the breaking sound and the load-deflection curve. A detailed diagram outlining the TI calculation is shown in Figure 2. In this study, the TI of FRCC-CR was calculated using the area under load deflection curve at the first crack (W_e) divided by the total area under load deflection curve up to 70% down from peak load (W_f), as given by the equation of toughness index.

$$\eta = \frac{Wf}{We} \quad (26, 27). \qquad [1]$$

The area of the opening displacement crack (OCD) is denoted by W_f and is calculated as 0.3 times the maximum load under the load deflection curve. The elastic energy consumption of FRCC-CR materials is represented by W_e and is determined by the area of OAB within the first crack zone. The TI for each specimen is determined using the ratio between the post-peak toughness and the pre-peak (elastic) toughness, based on the methods described in (28), JSCE-SF4 (29), and ASTM C1018 (30).

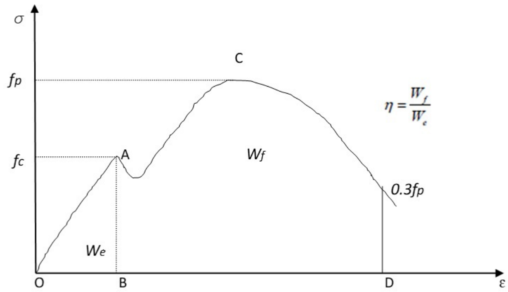


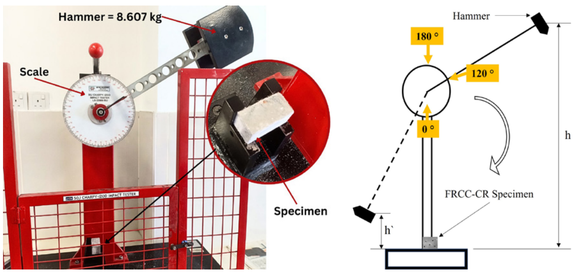
Figure 2. Diagram of the toughness index of FRCC-CR (reproduced from (26)).

2.3.4. Charpy impact

In this study, the Charpy impact test was utilized to determine the impact energy absorption (IEA) capacity of cementitious composite specimens subjected to an impact load, with the resulting IEA values expressed in joules per unit area of the specimen's cross-section. The test procedure is based on EN 10045-1 (31). The Charpy impact test device and its working scheme are shown in Figure 3, while Figure 4 illustrates the specimen dimensions and the impact loading configuration. The specimens used for the Charpy impact test had dimensions of 50 mm × 25 mm × 25 mm, maintaining a ratio of 1:1:2 (width: depth: length), as suggested previously (32). A total of 12 specimens for each mix were evaluated to obtain the experimental results, and the average results were reported. To calculate the IEA of the specimens, the following equation was used (32):

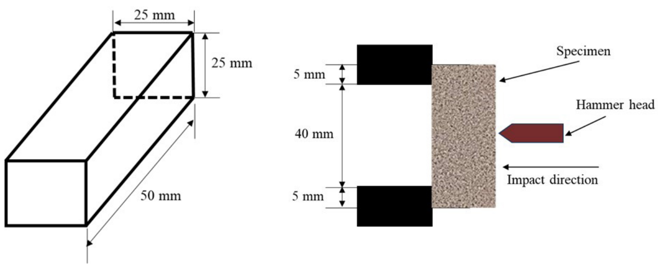
$$E = mgh - mgh` \qquad [2]$$

where,
E = Energy absorbed by the specimen (J),
m = mass of pendulum (kg),
g = acceleration of gravity (m/s^2),
h = height of pendulum starting point (m)
h` = height of pendulum ending point (m)



(a) (b)

Figure 3. Charpy impact test device used in this study (a) and its working scheme (b).



(a) (b)

Figure 4. Dimensions of specimen (a) and the configuration of impact loading (b).

2.4. Statistical analysis

The two-way ANOVA test was employed for statistical analysis in this study, utilizing the Statistical Package for the Social Sciences (SPSS), commonly referred to as IBM SPSS Statistics, version 25 (41). The experimental results underwent statistical analysis, with the data being drawn from the outcomes of the compressive test, flexural test, and Charpy impact test, respectively. Three variables (PVA, CR, and CR size) were examined in this two-way ANOVA test, serving as independent variables, while the impact energy absorption results were considered the dependent variable. The confidence level set for this test is 95%, indicating a significance level of p-value < 0.05 (α value). The independent variables are described as follows:

1. PVA (1.0%, 1.5%, 2.0%)
2. CR content (0%, 5%, 10%, 15%)
3. CR sizes (2 mm, 5 mm)

The hypothesis test aimed to establish whether there were statistically significant differences in IEA among all variables, shedding light on how the three mentioned variables influence IEA. The null hypothesis posits that the mentioned independent variable has no significant influence, either independently or collectively, on compressive strength, flexural strength, and IEA. The alternative hypothesis suggests that the independent variable independently and collectively influences compressive strength, flexural strength, and IEA.

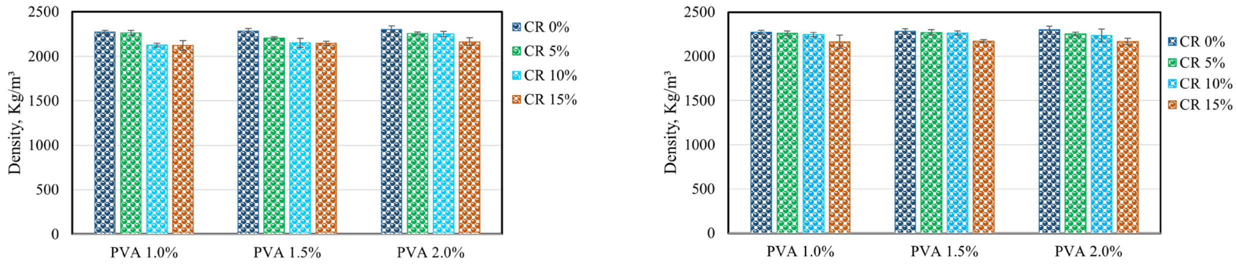
3. RESULTS AND DISCUSSION

3.1. Workability

The inclusion of fibres has a significant effect on the flow characteristics of cementitious composite mixes. The increment of PVA fibre content in the FRCC-CR mixes results in reduced workability. The increase in shear resistance to the flow of fresh cementitious composite mixes with substantially higher viscosities is the main cause of the workability reduction due to the addition of fibre. The large surface area of PVA fibre also leads to aggregation tendency, which further decreases workability (1). In this study, an appropriate amount of SP was required to offset the negative impact of fibre addition, and similar findings have been reported in other studies (1, 23). SP dosages of 0.4%, 0.5%, and 0.6% were used to maintain a constant flow diameter (170 ± 10 mm) for 1.0%, 1.5%, and 2% PVA fibre content, respectively. As the PVA fibre content increased in the FRCC, the SP content was adjusted accordingly to keep the flow within the specified range. This ensured that the workability data remained consistent and did not fluctuate significantly due to the varying SP percentages, as shown in Table 1. Nevertheless, no significant change in workability was observed upon incorporating CR in the mixes.

3.2. Density

The addition of CR has an impact on the hardened density of FRCC-CR mixes, as shown in Figure 5, where the overall density was found to decrease for all mixes when sand was substituted by CR. In Figure 5(a), with 2% PVA fibre present in the FRCC mixes, the density decreases by 2%, 2.2%, and 6% upon incorporating CR at 5%, 10%, and 15%, respectively, with a maximum particle size of 2 mm. In Figure 5(b), with 2% PVA fibre present in the FRCC mixes, the density decreases by 2.1%, 2.9%, and 5.8% upon incorporating CR at 5%, 10%, and 15%, respectively, with a maximum particle size of 5 mm. The overall density of the mixes decreases, with higher porosity introduced by the incorporation of CR being one of the reasons. The addition of CR creates additional void spaces within the specimen, resulting in increased porosity, as shown in (33, 34). Furthermore, the density decreased due to the different specific gravity; the specific gravity of CR is 1.15, which is lower than that of the fine aggregates (2.61). These findings agree well with related studies where CR has been used as an aggregate in concrete and mortar mixtures (6, 33-35). Based on the comparison of the effects of two sizes of CR shown in the figures, it was observed that FRCC-CR with maximum size of 2 mm has a slightly lower density than FRCC-CR with maximum size of 5 mm. This can be attributed to the higher porosity introduced by the smaller size of CR. Smaller-sized CR results in a greater number of particles with a higher surface area. On the other hand, the effect of fibres on density was found to be insignificant.



(a) (b)

Figure 5. Density of FRCC containing (a) CR size 0.5 – 2 mm and (b) CR size 2 – 5 mm at 28 days.

3.3. Compressive strength

Figure 7 illustrate the effects of CR and PVA fibre on the compressive strength of all mixtures at 28 days. The compressive strengths of the mixtures range from 60.2 to 88.3 MPa at 28 days. As depicted in Figure 7(a), when utilizing 2% PVA fibre in the FRCC mixes, the compressive strength decreases by 11.4%, 24.5%, and 31.8%, respectively, upon incorporating CR at 5%, 10%, and 15% with a maximum particle size of 2 mm, compared to their respective control mixes (without CR). Similarly, in Figure 7(b), with 2% PVA fibre utilization in the FRCC mixes, the compressive strength experiences reduction of 11.5%, 15.7%, and 24% upon incorporating CR at 5%, 10%, and 15%, respectively, with a maximum particle size of 5 mm. The observed decrease in compressive strength concurs with findings from prior research (1, 15, 33, 36). As shown in Figure 7, the overall trend of compressive strength decrease for all mixes compared to the respective control mixes; the factors are as follows (1, 15): (1) the hydrophobic nature of CR particles hinders effective bonding with the FRCC matrix, leading to a weakened interfacial transition zone (ITZ), as illustrated in Figure 6; (2) CR particles have lower compressive strength than the surrounding cementitious matrix, resulting in cracks in the contact zone and causing a fracture at the CR-cement matrix contact zone; (3) CR particles have a lower density than natural fine aggregates, thereby reducing the compressive strength of FRCC-CR.

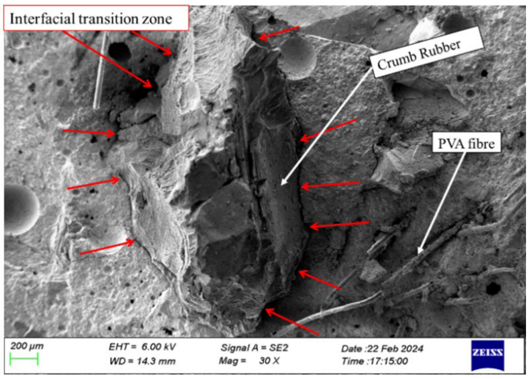
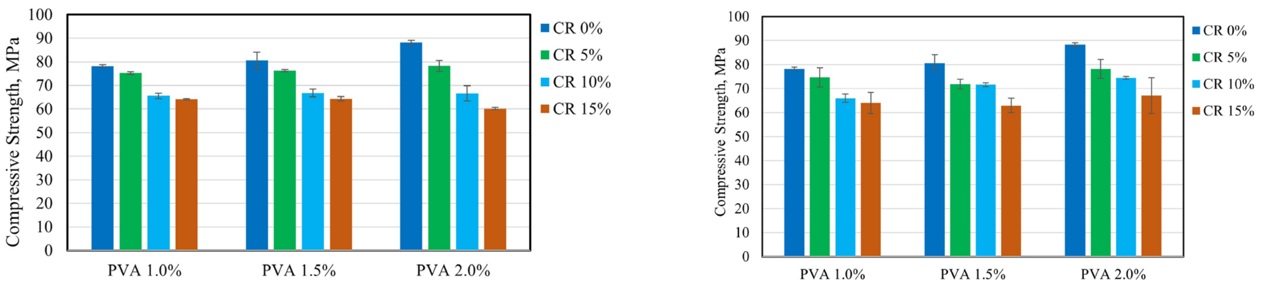


Figure 6. FESEM micrograph of FRCC-CR specimen, highlighting the ITZ.

Comparing the sizes of CR, Figure 7 shows that FRCC-CR with a maximum size of 5 mm exhibits lesser reduction in compressive strength than its respective control specimen (without CR) compared to FRCC-CR with a maximum size of 2 mm, at the same amount of CR and PVA fibre. This can be attributed to the difference in surface area between the two CR sizes; the total number of CR particles in the mixture is higher for CR with a maximum size of 2 mm compared to CR with a maximum size of 5 mm. As a result, the contact zone is increased, potentially resulting in a greater strength reduction in the former mix due to the water-repelling behaviour of CR.

The compressive strengths are quite similar for cementitious composites using PVA fibre content of 1.0% and 1.5%. When the PVA fibre content was increased to 2%, the compressive strength showed a slight increase as Figure 7 shown. This improvement in compressive strength with higher PVA fibre content can be attributed to the enhanced tensile strength of the fibre composite, which mainly depends on the bonding force between the fibre and cement matrix (28). PVA fibres have the ability to bridge micro-cracks and prevent their propagation, leading to a more homogeneous distribution of stresses within the composite, as reported by (37, 38). However, the primary goal of adding fibre to cementitious composite is not to increase compressive strength but to control cracking.



(a) (b)

Figure 7. Compressive strength of FRCC containing (a) CR size 0.5 – 2 mm (b) CR size 2 – 5 mm at 28 days.

3.4. Flexural strength

The flexural strength results are presented in Figures 8(a) and 8(b). The flexural strength increases when the amount of PVA fibre increases in the FRCC-CR mixes. However, incorporating CR in FRCC generally resulted in a slight decrease in flexural strength, with no consistent trend observed across all mixes compared to the respective control specimens. As depicted in Figure 8(a), with the utilization of 2% PVA fibre in the FRCC mixes, the flexural strength decreases by 14.7%, 18.4%, and 8.6% upon incorporating CR with maximum size of 2 mm at 5%, 10%, and 15%, respectively. According to Figure 8(b), when using 2% PVA fibre in the FRCC mixes, the flexural strength remains relatively stable with 5% and 10% CR content but decreases by 6.6% when CR is incorporated at 15%, with a maximum particle size of 5 mm, compared to the control mixes (without CR). The observed decrease in flexural strength and load capacity is consistent with earlier research (1,6,33,34); it can be ascribed to the same reasons that led to reduced compressive strength in the FRCC-CR mixes.

Comparing the two sizes of CR, the 2% PVA in FRCC-CR with a maximum size of 5 mm exhibits higher flexural strength than the corresponding FRCC-CR with a maximum size of 2 mm, whereas the difference is insignificant for 1% and 1.5% PVA FRCC. The improvement in flexural strength can be attributed to the bridging effect of PVA fibres, in addition to the contribution of larger CR particles in enhancing the flexural strength of FRCC-CR, facilitating a more effective load transfer mechanism. Figure 8 shows that the flexural strength of FRCC-CR significantly increased with increasing PVA dosages. The flexural strength values were found to be 17.9 MPa, 19.2 MPa (a 7.3% increase), and 31.4 MPa (a substantial 74.8% increase) when PVA was used in the cementitious composite (without CR) at dosages of 1%, 1.5%, and 2%, respectively. The effects of PVA dosages on flexural strength in FRCC-CR mixes were observed as the fibre content increased from 1% to 2%, resulting in an average increase of 83% and 93% for CR size 2 mm and CR size 5 mm, respectively, regardless of the CR dosages and sizes. Adding more PVA fibres up to an optimum value resulted in better bridging effect, enhancing the multiple cracking processes, and leading to an improvement in strength, as reported by (18, 38, 39).

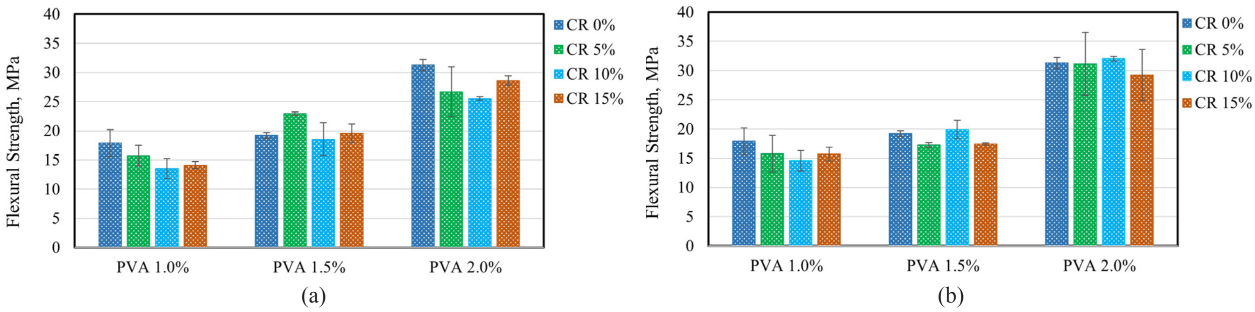


Figure 8. Flexural strength of FRCC containing (a) CR size 0.5 – 2 mm (b) CR size 2 – 5 mm at 28 days.

3.5. Load-Deflection

Figure 9 illustrates the load-deflection curve of FRCC prism specimens at 28 days, containing varying levels of CR as a partial replacement for fine aggregate and reinforced with PVA fibres. As indicated by the figures, the deflection values observed at the point of peak load were 0.73 mm, 0.67 mm, and 0.73 mm when incorporating 5%, 10%, and 15% CR with a maximum size of 2 mm and 2% PVA fibre, respectively. Similarly, the deflection values at the maximum load were 0.80 mm, 0.74 mm, and 0.82 mm with CR incorporation of 5%, 10%, and 15% with a maximum size of 5 mm, along with 2% PVA fibre in the FRCC, respectively. Interestingly, no significant difference was observed in the deflection among the various CR incorporation percentages. However, the noteworthy observation is that CR with a larger maximum particle size of 5 mm consistently exhibited higher ultimate load capacity and corresponding deflection compared to CR with a maximum size of 2 mm. This trend suggests that utilizing larger CR particle sizes could enhance energy absorption and deflection capacities of the FRCC-CR mixtures. Consequently, these findings underscore the advantageous nature of including CR as fine aggregates in FRCC mixtures, particularly when seeking improved deflection capabilities (6). Additionally, Figure 9 shows that the dotted line is higher at 9(c) compared to 9(b) and 9(d). This indicates that the 1.5% PVA fibre does not establish a consistent trend with CR-5, whereas the 2% PVA fibre results in a consistent dotted line, suggesting it is the optimal concentration.

Additionally, Figure 9(a) shows that incorporating 1% and 1.5% PVA fibres into the FRCC mixes resulted in similar ultimate load and corresponding deflection. However, when the PVA fibre content was increased to 2%, both maximum load and the corresponding deflection exhibited concurrent increase. Figures 9(b), 9(c), and 9(d), also demonstrate higher deflection values at the peak load when there is higher PVA content incorporated in the FRCC-CR mixes. The incorporation of PVA fibres resulted in a diminished macro-crack width, underscoring the synergistic interplay between CR and FRCC that effectively curbed crack propagation (1). The following load-deflection curves use blue for 1%, orange for 1.5%, and green for 2% PVA fibre. Solid curves represent CR size 2, while dotted curves represent CR size 5. For the load-deflection curve, one curve was selected from two similar specimens, or three if they were close, as calculating an average value was not deemed suitable.

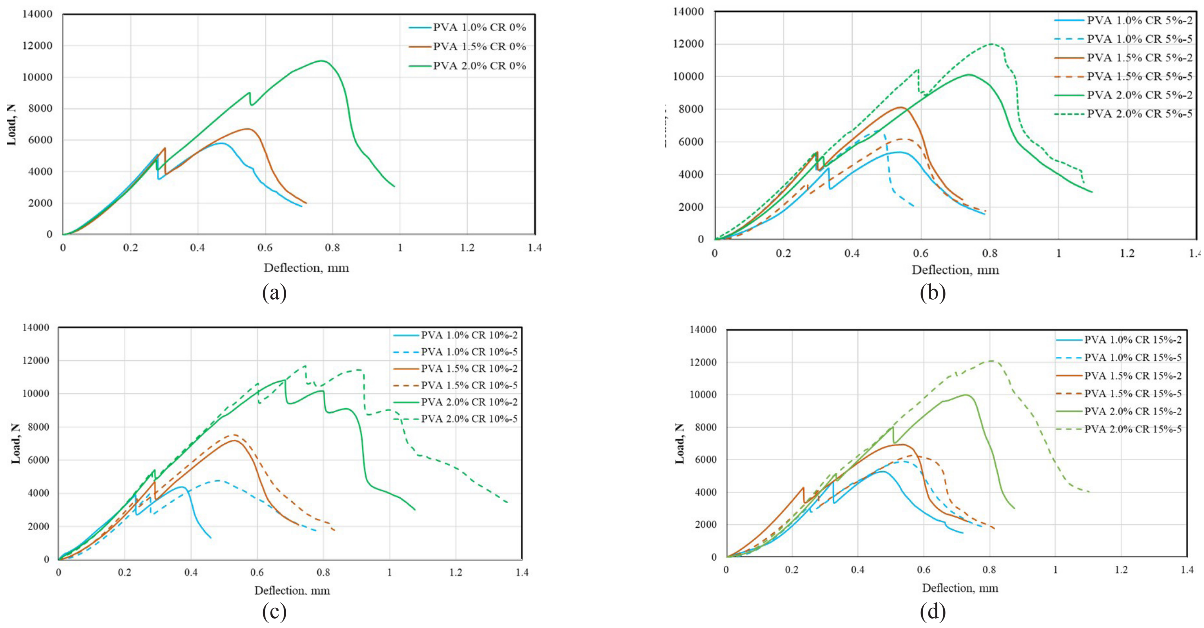


Figure 9. Flexural load vs deflection curves of FRCC-CR incorporated with 1.0%, 1.5% and 2% PVA for CR size 0.5 mm to 2 mm and 2 mm to 5 mm: a) Control, b) CR5, c) CR10 and d) CR15.

3.6. Toughness index

The toughness index (TI) is a metric that provides a reliable and quantifiable measure of the energy absorption capacity of FRCC when CR is incorporated in these studies (1). It is a valuable tool for assessing the material's ability to withstand impact and absorb energy effectively. The toughness properties of a composite are essential as it enables a composite to exhibit a more conspicuous warning prior to failure, rather than experiencing sudden brittle failure (1). Figure 11 show a significant increase in the overall trend of TI when CR content was incorporated in FRCC mixes compared to control mixes (without CR). As illustrated in Figure 11(a), when 1.5% PVA fibre is utilized in the FRCC mixes, the TI increased by 16.8%, 41.2%, and 59.2% upon incorporating CR (maximum size of 2 mm) at 5%, 10%, and 15%, respectively. In Figure 11(b), with the utilization of 1.5% PVA fibre in the FRCC mixes, the TI increased by 58.4%, 66.2%, and 44.1% upon incorporating CR (maximum size of 5 mm) at 5%, 10%, and 15%, respectively, compared to their respective control mixes (without CR). The observed improvement in the TI is attributed to the ability of CR particles to deform both elastically and plastically. Initially, CR particles absorb energy through elastic deformation. As the load increases, they undergo plastic deformation, dissipating energy and delaying crack widening. This allows the specimen to sustain significant deformations without complete disintegration, as the elasticity of CR particles helps the material absorb energy and undergo higher strain levels, thereby enhancing its overall toughness (1, 6). FESEM micrographs of the PVA fibre in the control specimen are shown in Figure 10(a), while micrographs of both the fibre and CR simultaneously present in the specimen are displayed in Figure 10(b).

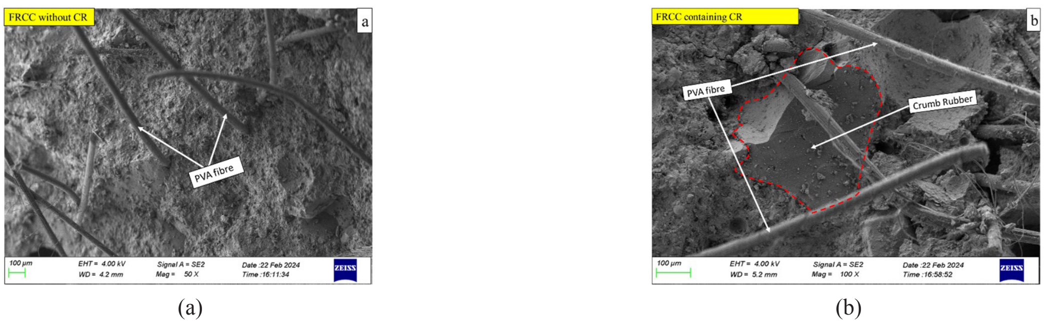
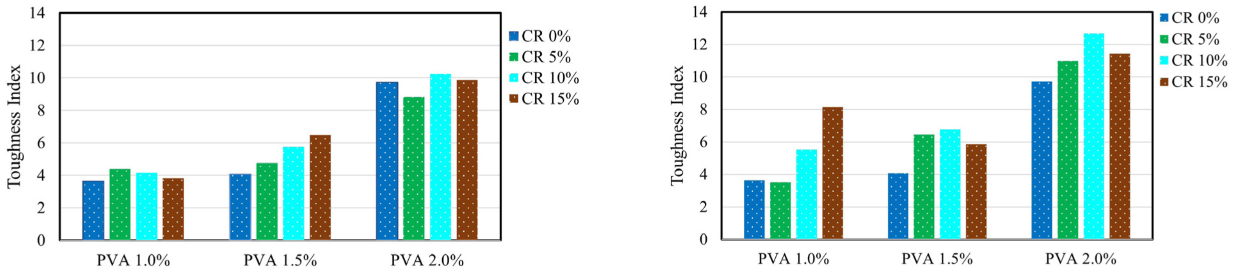


Figure 10. FESEM micrographs of specimen; (a) FRCC without CR (b) FRCC containing CR.

Figure 11 shows that FRCC-CR with a maximum size of 5 mm and incorporating 2% PVA fibre, exhibits higher toughness compared to the FRCC-CR with a maximum size of 2 mm. The smaller size CR particles cause adverse effects due to the following reasons: (1) a larger contact surface area between the CR and the cementitious matrix, leading to higher stress concentration and susceptibility to cracking, and (2) a higher volume fraction of smaller CR particles hindering stress distribution and resulting in localized stress concentrations and reduced overall toughness. The figures clearly show that TI increases in FRCC-CR mixes when PVA fibre content is incorporated. For instance, the TI increases on average by around 128% when the PVA fibre dosage is increased from 1% to 2% in the FRCC-CR, regardless of CR size and content. The increase in toughness due to the inclusion of PVA fibre is consistent with the findings of previous studies (1,6,28). The incorporation of fibres leads to enhanced initial and ultimate energy absorption owing to their ductile properties and ability to induce fibre-bridging effects within the specimen (34). This study therefore suggests that incorporating 2% PVA fibre and 10-15% CR can enhance deflection capacity and improve overall toughness in the FRCC.



(a) (b)

Figure 11. Toughness index of FRCC containing (a) CR size 0.5 – 2 mm (b) CR size 2 – 5 mm at 28 days.

3.7. Charpy impact

The investigation into the impact energy absorption (IEA) of FRCC-CR is illustrated in Figure 12. The results indicate that the incorporation of CR in place of fine aggregate led to an increase in IEA. The figures clearly demonstrate a consistent rise in the overall IEA trend for FRCC mixes containing CR, compared to their respective control mixes (without CR content).

As depicted in Figure 12(a), when 2% PVA fibre is utilized in the FRCC mixes, the IEA increased by 2.2%, 3.2%, and 5.6% upon incorporating CR (maximum size of 2 mm) at 5%, 10%, and 15%, respectively. From Figure 12(b), in the 2% PVA FRCC mixes, the IEA increased by 3.7%, 3.8%, and 11.9% upon incorporating CR (maximum size of 5 mm) at 5%, 10%, and 15%, respectively. The FRCC-CR has enhanced the IEA capacity of the composite, as CR particles increase the ability of the composite to absorb (1) and dissipate energy (34). A transgranular effect (dynamic behavior) is characterized by its sudden application and short duration, where the material's interface (bonding) lacks sufficient time to transfer the load, unlike in the intergranular effect (quasi-static behavior) involving flexure or compression. Therefore, the bond strength between materials has a smaller impact on the IEA compared to the inherent properties of the material body. The cracking path of the specimen due to flexural loading follows the bonding interface, whereas the cracking path of the specimen due to impact load passes the CR material itself (Figure 13). The addition of CR particles to the exposed surface of the composite can also increase impact resistance. When the Charpy impact head strikes a deformable surface, it facilitates energy absorption because CR particles are resilient, elastic (34), and have low stiffness (more flexible or less rigid) (40).

Furthermore, the sizes of the CR particles play an important role in determining the IEA of the FRCC mixture. Specifically, CR with a maximum size of 5 mm has been found to have better IEA performance than CR with a maximum size of 2 mm, as the larger particles can resist or fracture more slowly when the impact head strikes the deformable surface. This mechanism accelerates the consumption of energy, enabling the CR to absorb impact energy through deformation before the failure of debonding and cracking of the specimen. The maximum IEA value observed was 0.054 (J/mm^2) when 2% PVA and 15% of CR with a maximum size of 5 mm were incorporated into the mix, which was 12% greater compared to their control specimen.

As seen in Figure 12, there is a clear relationship between impact energy and the increase in fibre volume ratio. Notably, the IEA experienced a significant 38% improvement as the PVA fibre content increased from 1% to 2% in the FRCC mixes. This phenomenon can be explained by the following factors: (1) The addition of PVA fibres to the FRCC-CR greatly enhances its IEA, mainly because it toughens the composite. (2) PVA fibres have good tensile strength, which enables them to effectively absorb energy by creating bridges across the cracks that appear in the composite under impact loading. (3) The inclusion of PVA fibres contributes to a reduction in the inherent brittleness of the FRCC, thereby lowering its vulnerability to sudden and catastrophic failure.

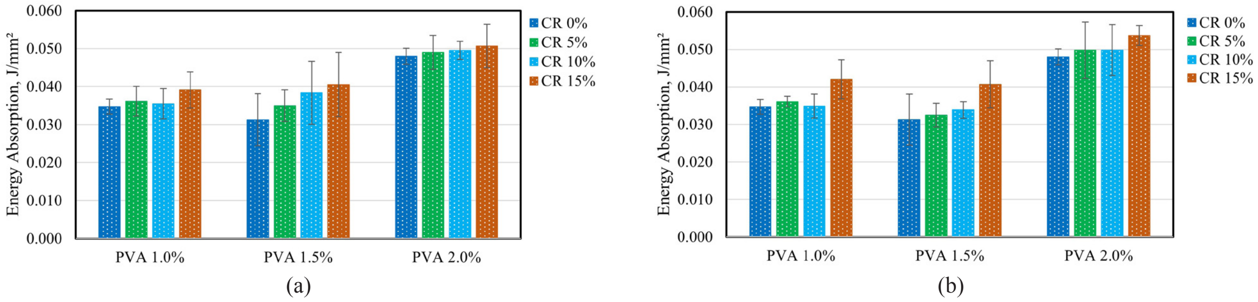


Figure 12. Impact energy absorption of FRCC containing (a) CR size 0.5 – 2 mm (b) CR size 2 – 5 mm at 28 days.

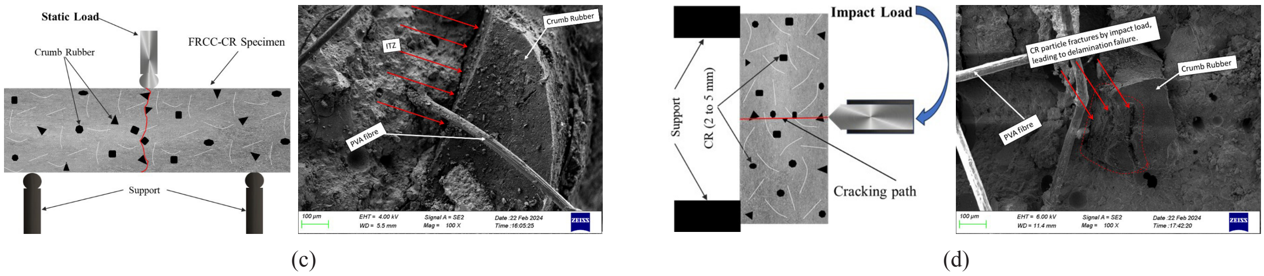


Figure 13. Crack pattern observation (a) flexural test (b) FESEM of corresponding specimen (c) Charpy impact test (d) FESEM of corresponding specimen.

3.8. Statistical analysis

In the studies, statistical analyses were conducted using a two-way analysis of variance (ANOVA) to examine the influence of mixing variables (specifically, PVA fibre contents, CR contents, and CR sizes) on the compressive strength, flexural strength, and IEA within FRCC mixtures. Statistical analyses were conducted using data obtained from previous experimental results. In this test, a confidence level of 95% is practiced, meaning that the p-value is < 0.05 (α value). The results of the two-way ANOVA test are presented in Table 2, where compressive strength, flexural strength and IEA play as the dependent variables and PVA fibre content, CR content, and CR sizes as independent variables. The null hypothesis questioned whether PVA fibre content, CR content, and CR size individually influence compressive strength, flexural strength, or IEA, as well as the combined effect of PVA fibre and CR in FRCC. Conversely, the alternative hypothesis proposed that both the individual PVA fibre content, CR content, and CR size exert an influence on compressive strength, flexural strength, or IEA, as well as the combined effect of PVA fibre and CR in FRCC.

The 'Corrected Model' in ANOVA assesses the model's fit, indicating that if the *p*-value is less than 0.05, the model significantly explains the variability, with at least one independent variable influencing the dependent variable, whereas a p-value greater than 0.05 suggests the model does not significantly explain the variability. As shown in Table 2, the *p*-values of the corrected models are 0.00 (< 0.05), suggesting a significant overall model fit and indicating that at least one of the independent variables significantly influences compressive strength, flexural strength, and IEA, respectively. The F-ratios correspond to each independent variable (PVA, CR, and CR Size), indicating the strength of their effects on the dependent variables. The R-squared values indicate that approximately 84%, 91%, and 54% of the variability in compressive strength, flexural strength, and IEA, respectively, are explained by the included independent variables in the model. The *p*-value of 0.00 was obtained directly from the ANOVA test results, reflecting the statistical calculation performed by the software.

The ANOVA results indicate that PVA fibre contents, CR contents, and CR sizes each individually influence compressive strength, as evidenced by their respective p-values being less than 0.05. However, the interaction between PVA and CR does not appear to be statistically significant (p-value > 0.05), suggesting that their combined effect may not significantly influence compressive strength. This could be due to opposing or neutralizing effects, meaning they might counteract each other. For instance, while one enhances strength, the other might diminish it. From the experimental results (Figure 7), it was determined that PVA fibre slightly increased compressive strength, whereas the inclusion of CR content in FRCC decreased compressive strength significantly.

For the flexural strength, the PVA fibre (p-value = 0.00) exhibits a highly significant impact on flexural strength, suggesting a substantial role in increasing flexural strength in FRCC mixes. Conversely, CR (p-value = 0.564) and CR sizes (p-value = 0.233) in FRCC do not individually influence flexural strength, as their p-values exceed 0.05. Additionally, the combined effect of PVA fibre and CR does not significantly impact flexural strength, either by increasing or decreasing it, as the p-value surpasses the significance level of 0.05. The above finding is supported by earlier research as reported by Lye et al. (18) and Manfaluthy and Ekaputri (38).

While for IEA, all PVA fibre (p-value = 0.00), CR content (p-value = 0.009), and CR sizes (p-value = 0.019) significantly influence IEA. However, when PVA fibre and CR are combined, they do not collectively influence IEA in FRCC-CR. This could be attributed to those mixtures containing 1% and 1.5% of PVA fibre may not achieve the optimal combination that maximizes IEA in FRCC-CR, which affects the overall statistical results of the combined effect. The experimental results in Figure 12 reveal a significant increase in IEA when specific fibre doses (2% of PVA fibre) were increased in FRCC, with a simultaneous increase in CR content up to 15%.

Finally, a summary gleaned from the statistical analysis of compressive strength, flexural strength, and IEA of FRCC-CR indicates several noteworthy trends. The inclusion of CR correlates with a decrease in compressive strength, a decline that is statically countered by the presence of PVA fibre. While PVA fibre contributes to the enhancement of flexural strength, the incorporation of CR does not exert a statistically significant influence on flexural strength. Moreover, the introduction of CR in FRCC results in a static increase in IEA. Notably, even with an increase in PVA fibre volume, the simultaneous presence of both materials maintains a consistent increase in IEA. Statistical analyses show that CR size influences the respective results, meaning that CR with a maximum size of 5 mm demonstrated slightly better performance compared to CR with a maximum size of 2 mm in compressive strength and IEA.

Table 2. Statistical results by two-way ANOVA tests.

Test	Source	F - Ratio	*P*- value	R Squared
Compressive strength	Corrected Model	11.4	0.000	0.84
	PVA	3.5	0.035	
	CR	36.4	0.000	
	CR Size	13.9	0.000	
	PVA*CR	1.9	0.099	
Flexural strength	Corrected Model	17.1	0.000	0.91
	PVA	133.4	0.000	
	CR	0.6	0.564	
	CR Size	1.5	0.233	
	PVA*CR	0.3	0.894	
Impact energy absorption	Corrected Model	12	0.000	0.54
	PVA	23.1	0.000	
	CR	7.3	0.009	
	CR Size	4.2	0.019	
	PVA*CR	0.4	0.680	

4. CONCLUSION

In this study, the workability, mechanical properties, and impact energy absorption (IEA) of fibre reinforced cementitious composite (FRCC) containing two sizes (ranging from 0.5 to 2 mm, and from 2 to 5 mm) of crumb rubber (CR) with 5%, 10%, and 15% contents were investigated. Polyvinyl alcohol (PVA) fibre was used as reinforcement in FRCC containing CR (FRCC-CR) at varying percentages of 1%, 1.5%, and 2%. The following main conclusions were drawn from the experimental results:

1. The inclusion of PVA fibre in FRCC-CR mixes reduced the workability, which was compensated by using the appropriate dosage of superplasticizer (SP). Specifically, the SP dosage of 0.4%, 0.5%, and 0.6% was used to maintain constant flow diameter for 1.0%, 1.5%, and 2% PVA fibre, respectively.
2. The addition of CR in FRCC mixes led to a gradual decrease in density. The maximum density decreased by approximately 6.7% when 15% CR with a maximum size of 2 mm was incorporated with 1% of PVA in the FRCC.
3. The overall compressive strength of the FRCC-CR decreased as the CR dosages increased. The greatest reduction in compressive strength was observed when 15% CR with maximum size of 5 mm was incorporated into the 2% PVA FRCC, resulting in a reduction of 31.8% (60.2 MPa).

4. The overall trend of the flexural strength of the FRCC-CR generally decreases with the incorporation of CR content. However, the flexural strength increased around 54% when PVA dosages increased from 1% to 2% in FRCC containing 15% of CR with a maximum size of 5 mm.
5. Mid-span deflection significantly increased with the increasing CR content in 2% PVA FRCC mixes, demonstrating that incorporating CR as fine aggregates in FRCC mixtures could improve the deflection capacity.
6. The toughness index (TI) increased compared to their respective control specimens. The highest TI value of 12.7 was observed when 10% of CR with maximum size of 5 mm was incorporated in 2% PVA FRCC mixes, which was increased by around 30% compared to the control specimen.
7. The IEA capacity via the Charpy impact test, increases in all mixes containing CR in FRCC. The highest IEA value of 0.054 (J/mm^2) observed when 15% of CR with maximum size of 5 mm was incorporated in 2% PVA FRCC mixes, representing an increase of around 12% compared to the control specimen.

Statistical analysis using a two-way ANOVA test was conducted utilizing experimental data and the following conclusions are drawn:

a. PVA fibre demonstrated a significant increase in compressive strength, whereas CR exhibited a significant decrease in the compressive strength of FRCC-CR.
b. PVA fibre significantly enhanced the flexural strength of FRCC-CR, while CR showed no significant influence on flexural strength.
c. All PVA fibre, CR content, and CR sizes individually exhibited significant effects on the IEA results in FRCC-CR

Overall, the results suggest that the incorporation of CR and PVA fibre in FRCC mixes can present challenges in terms of the workability and mechanical properties of the composite. However, the addition of CR as partial fine aggregate replacement in FRCC mixtures can enhance the deflection capacity, toughness, and IEA, which could be beneficial for certain applications. Moreover, CR and PVA fibre in FRCC statically influence IEA according to the statistical analysis.

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Kim Hung Mo: Conceptualization; Resources; Supervision and Editing.
Chee Ghuan Tan: Conceptualization; Supervision; Funding acquisition and Editing.
Haider Hamad Ghayeb: Resources; Validation and Editing.

Data and code availability:

This research contains various types of experimental data, and their availability is subject to demand.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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