Impact Properties of Hemp Fibre Reinforced Cementitious Composites

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Abstract. The construction industry has seen an incredibly fast increase in utilizing natural fibres for making low-cost building materials to achieve sustainable construction. One of such applications is natural fibre-reinforced cementitious materials for either structural or non-structural purpose. Impact properties are engineering properties received increasing attentions from engineering community for structural materials. This research therefore studies impact resistance of hemp fibre reinforced cementitious composites at early ages. Hemp fibre with various lengths, 10 mm and 20 mm, are utilized to reinforce cementitious materials. Hemp fibre reinforced cementitious composite slabs were tested under repeating dropping mass till failure at the age of 7, 14 and 28 days. Cracking behaviour, impact resistance, absorbed impact energy and survived impact blows upon failure are qualitatively/quantitatively analysed. It has been found that 20 mm-long hemp fibre reinforcement leads to higher impact resistance, more absorbed impact energy and survived more impact blows upon failure. Cementitious composite slabs reinforced by 20 mm-long hemp fibres exhibit higher impact crack resistance ratio than those reinforced by 10 mm-long fibres. Longer fibres are more effective in inhibiting the growth of micro-cracks and blunting the propagation of micro-cracks before they join up to form macro cracks leading to ultimate failure.

Introduction

Nowadays one of the main challenges of the construction industry is to improve its image in terms of sustainability. As a result, the construction industry has seen an incredibly fast increase in utilizing natural fibres for making low-cost building materials and products for construction. Increasing concern about the sustainability and economics in many developing countries, where natural fibres of various origins are abundantly available, encourage engineers to employ appropriate technology to utilize natural fibres and local materials as effectively, economically and much as possible for construction. This paper studies the impact properties of short discrete hemp fibres reinforced cementitious composites (HFRCs). Hemp is a member of the family Cannabis and is thought to be a very useful and sustainable building material as it is known to be one of the fastest growing biomasses. Hemp fibres are obtained through a series of process on the stalks including retting, drying, crushing and shaking process separating fibres from woody portion. The fibre strands are made of individual cylindrical cells with an irregular surface, usually over 1.8 metres long [1]. High strength, durability, low density, biodegradability and being environmentally friendly and carbon negative associated with hemp fibres has led into increase in the use of them in the manufacture of composite materials.

On the other hand, concrete structures may be subjected to impact loads during their life span. Modern concrete construction always requires fast mould strip and concrete at early ages are more vulnerable to impact load. It is essential to enhance the resistance of concrete structures including at early ages under impact loads by applying different applications of reinforcement such as inclusion of fibres. Natural fibres have the potential to be used as reinforcement to overcome the inherent deficiencies in cementitious materials [2]. In this research, repeating drop weight impact test method has been employed to investigate behaviour of HFRC panels. The impact test results were analysed by a method combining the approaches proposed by Siddque [2] and Zhou et al. [3].

Materials and Methods

Raw materials and mix proportions. The basic mix proportion for HFRC was Binder: Sand: Aggregate = 1:1.5:2.5 by weight with the water-to-binder (W/B) ratio equal to 0.68. The binder consisted of Portland Cement (PC) and Ground Granulated Blast-furnace Slag (GGBS) at 50%: 50%-based by weight. CEM II PC (from LAFARGE Cement UK) compatible with EN 197-1 was used as binder for preparing HFRC. The specific gravity density of the CEM II PC was 2.96 with Blaine fineness (specific surface area) of 423m^2/Kg measured conforming to EN 196-6. GGBS was obtained from Hanson Heidelberg Cement Group (UK), which is compliant with EN 15167-1 for use as a type II addition in the production of concrete. The specific gravity density and Blaine fineness of the GGBS used for this project were tested conforming to EN 196-6 with the value of 2.93 and 512m^2/Kg, respectively. Shingle with 10-mm maximum particle size and river sand with 2-mm maximum grain size was used as coarse and fine aggregates, respectively. Both fine and coarse aggregates were pre-heated in an oven with the temperature of 105 ºC for 24 hours to eliminate any moisture assimilated prior to concrete casting. They were then cooled down in air for 2 hours before they were used for concrete mix. Hemp fibres were obtained from KJVoase farm based in East Yorkshire, UK in collaboration with the European Industrial Hemp Association (EIHA). The provided hemp fibres, as bunch of long fibres with more than 1 meter long, were completely natural with no pre-treatment and they were chopped manually using a pair of scissors to the designated length of 10 and 20 mm.

Sample preparation & testing. Hemp fibres were presented in HFRC mixtures at the volume ratio of 1% with the fibre length of 10 or 20 mm. For each scenario (different fibre lengths at different ages), six Φ100×200 mm cylinders for compressive and splitting tensile strength measurement, three for each, and four panels, with the dimensions of 300×300 mm^2 and 40 mm thick, for impact resistance test were prepared. The specimens were initially cured for 24 hours in mould covered with polyethylene sheets in room temperature. Then the moulds were stripped off and the specimens were moved into a curing cabinet with the temperature 20 ± 1 ºC and relative humidity 95%.

Compressive strength of HFRCs was tested conforming to EN12390-3 on cylinders at the ages of 7, 14 and 28 days under a constant loading rate of 4.7kN/s. Splitting-tensile strength of HFRCs were measured conforming to BS EN 12390-6 also from cylindrical specimens at the ages of 7, 14 and 28 days under a constant loading rate of 1.2kN/s.

Repeated drop weight method was employed to investigate impact resistance of HFRCs on panels. The repeated drop weight impact test set-up is shown in Fig 1. The testing system consisted of a stainless steel rod as the drop weight of 6 kg from the height of 0.8 m with a cylindrical body diameter of 4 cm which was connected to a tensile wire that can be manually controlled, and kept vertically by a steel wire fixed to the pulley installed on frame. Steel rod front head had a spherical shape and the impact surface area had been reduced from the diameter of 4 cm into 2 cm, which modified it to act more as a point load at the moment of impacting. A central impact was achieved by means of a plastic

Figure 1 Impact resistance test set up including oscilloscope

tube guide. The guide tube had an inner diameter greater than that of the ball in which the projectile was allowed to slide freely up and down with no friction between them. Additionally, the inside surface of the plastic tube was lubricated in order to prevent any friction between the tube guide and the steel rod.
HFRC panels were placed on a steel base plate, which was fixed to the vertical steel frame. Two oscilloscopes were used to monitor the chosen physical parameters. One oscilloscope was connected to an accelerometer, which was mounted underneath the centre of the steel base plate. Voltage signals were picked up by the accelerometer and presented on oscilloscope so that it could be used to calculate the energy absorbed by HFRC panels at each blow. In addition, the projectile was equipped with an accelerometer, which was connected to the other oscilloscope in order to measure the impact load. Applied impact load was determined by multiplying the deceleration and mass of the projectile. In this study, for the impact resistance tests carried out, all HFRC panels were subjected to impact at their centre point of 300×300 mm^2.
Based on the assumptions for the semi-quantitative analysis of impact resistance test, the potential energy of the projectile was converted to kinetic energy and subsequently into signals, which was picked up by an oscilloscope. For each specimen, voltage obtained from the first impact was considered as a benchmark. During the test, notes were taken to record the number of blows required to initiate the first visible crack and the number of blows required to cause ultimate failure of a HFRC panel. The same impact test was carried on for a reference steel panel with the same dimensions as the HFRC panels. It was found from the test that the measured voltage by oscilloscope for impacted reference steel plate was always 270 V. In addition to results obtained by the oscilloscopes, judgment by naked eye was also used to identify failure of the HFRC panels. It has been suggested that concrete panels can be judged as failed when a visible crack propagate throughout the panel, i.e. "at least one crack propagated throughout the panel reaching any two opposite edges of the square panel and throughout the depth of the panel as well" [3]. The impact test was carried on until both failure criteria for obtained results from the oscilloscopes and judgment by eye observation were satisfied.

Data analysis methods. In general, there is a loss of potential energy in repeated drop weight impact test, which is absorbed and dissipated as strain energy, causing cracks in HFRC panels. The energy absorbed is dissipated in the form of crack patterns produced from the impact loading. The intensity of the energy, the amount of energy absorbed and the properties of the concrete determine the width of crack and its post crack behavior. The following quantitative parameters are analysed:
Impact crack resistance ratio C_r. In various analyses, C_r is defined as the relationship for the potential energy of an impact loading due to a falling body and the strain energy dissipted in cracks that develop in a target, which may be expressed based on fundamentals of strength of materials approach as (Kankam et al.):

$$N \times e = R_u l_c d_c w_c \, . \quad (1)$$

Where N = numbe of blows; e = energy per blow; R_u = ultimate crack resistance (in MPa) of material; l_c = total length of all cracks; d_c = maximum crack depth; and w_c = maximum crack width.
The ultimate crack resistance R_u can be determined from the above equation in order to determine the dimensionless impac crack resistance ratio C_r which is employed in this study to compare the abilty of HFRC panels to withstand impact cracking. The impact crack resistance ratio C_r can be determined using an equation propopsed [2]

$$C_r = R_u f_c \quad (2)$$

Where f_c is the compressive strength of the HFRC in this study.
Absorbed energy. In this study, absorbed energy by a HFRC panel at each impact blow can be characterised in terms of voltage from Eq. 3 employing drop weight apparatus, accelometer and oscilloscope for relative comparison purpose [3]. It should be noted here the absorbed energy here is

not a physical quantity but is generated purely for relative comparison purpose. This parameter allows semi-quantitative comparison of various HFRC panels in terms of their energy absorption.

$$EnergyAbsorbed = \frac{V_{REF} - V}{V_{REF}} \times mgh \quad (3)$$

In this equation, V_{REF} represents the voltage signal picked by the oscilloscope during the impact on the reference steel plate while the variable V represents the voltage signal picked up by the oscilloscope during each impact blow on a HFRC panel.

Residual Impact Strength Ratio I_{RS}. Every HFRC panel initiated the first visible crack after certain number of blows and followed by more blows to reach ultimate failure. Relationship among impact energy, energy absobed up to initiation of the first crack as well as at ultimate failure provides another index for evaluating performance of HFRCs under impact. This index is the Residual Impact Strength Ratio I_{RS} which is defined as following:

$$I_{RS} = \frac{EnergyAbsorbedatUltimateFailure}{EnergyAbsorbedatinitiationofthefirstcrack} \quad (4)$$

Impact load. In this research, acceleration of the projectile just before each imact can be obtained in terms of voltage, employing drop weight appartus, accelometer and oscilloscope. Subsequently the impact load was determined by multiplying the deceleration of projectile and mass of the projectile as $F = ma$, where F is the impact load; m is the mass of the projectile; and a is acceleration of projectile just before impact. This parameter is used in determining rate of energy absorption per impact load.

Rate of energy absoption per impact load. It is believed that deceleration of the projectile must remain constant for equal projectile mass dropped from the same height during their free fall, so absorbed energy will be measured under the constant impact load. However, as this experiment is operating manually, there are some sources of error. Therefore impact load applied on HFRC panels at each blow was determined, so their cumulative addition up to failure can be considered in comparison of their respective energy absorption up to failure. The following formula divides the residual energy absorption up to failure by residual impact load up to failure to determine rate of energy absorption per impact load, as a corrective measure for energy absorption.

$$\text{Rate of energy absorption per impact load} = \frac{\mathrm{Re}\,sidualEnergyAbsorptionuptoFailure}{\mathrm{Re}\,sidual\mathrm{Im}\,pactLoaduptoFailure} \quad (5)$$

Residual energy absorption up to failure stands for combination of absorbed energy at each impact up to failure of a specimen. Residual impact load up to failure also stands for a combination of impact loads at each impact up to failure of a specimen. Two oscilloscopes were used to monitor and record the chosen parameters. First oscilloscope was connected to an accelerometer, which was mounted underneath the centre of the base plate. Voltage signals were picked up by the accelerometer and presented on oscilloscope so that it could be used to calculate the energy absorbed by concrete specimens at each blow. The projectile was equipped with an accelerometer, which was connected to the second oscilloscope to measure the impact load. Applied impact load was determined by multiplying the deceleration of projectile and mass of the projectile.

Results and discussions

Compressive and splittin tensile strength. Compressive and splitting tensile strength of HFRCs reinforced fibres with 10 or 20 mm-long fibres at various ages is shown in Table 1. It can be seen that HFRCs reinfoced with 10mm-long fibres exhibit higher compressive strength than those reinforced with 20mm-long fibres, though the difference is marginal. On the other hand, HFRCs reinforced with 20 mm-long fibres exhibited higher splitting tensilse strength than those with 10 mm-long fibres at all three ages, indicating that splitting tensile strength increases with increase in fibre length. The presence of micro cracks at the cement paste-aggregate interface resulted in weakness of concrete while inclusion of fibres helped to transfer loads at the internal micro cracks. Also fibres can bridging cracks. Additionally, during the testing session it has been evident that HFRC cylinders with 20mm fibres cracked across the centre but cylinders did not broke in half completely as fibres were bridging cracks but with 10mm fibres this was less obvious.

Cracking behaviour. It has been evident that failure pattern and cracking behaviour of HFRC panels is similar under both fibre lengths of 10 and 20 mm, and is related to their respective age. Fig. 2 illustrates cracking behavior of HFRC with fibre length of 20 mm at ages of 7, 14 and 28 days. It can be seen that cracks for the specimen at the age of 7 days propagated in three directions from the centre of a panel to the middle of its sides with narrow crack width. At the age of 14 days wider cracks were formed which divided one corner of the panel by propagating from centre of the panel to middle of side edges showing more damage. At the age of 28 days most specimens were halved from centreline of the square panel with crack wider than that at 7 and 14 days. Additionally, in case of HFRC panels at 7 days, fibre pullout was observed at ultimate failure especially for those reiforced by 20 mm long fibres. At ages of 14 and 28 days, more fibres fractured than being putlled out at ultimate failure. These failure behaviours with ageing can be explained by two reasons. Initially, higher level of moisture due to the slower hydration process makes early age specimens more ductile, while specimens at age of 28 days are very brittle. Second reason is that alkali environment of HFRC led to deterioration of hemp fibres causing them to lose their functionality as reinforcement. At early ages, due to slower hydration process, alkalinity in HFRC was not strong, resulting in less deterioration of fibre structures while with ageing of specimens higher rate of alkali reactions with hemp fibre lignin will occur. Furthermore, generally crack width increased with increase in curing age. For instance, crack width at 28 days were almost twice as crack width at 7 days. It has also been noticed that specimens reinforced with longer fibres regardless of their age provided better post cracking behaviour as they tended to reduce further increase in overall crack width by bridging them. Despite the fact that both types of specimens did have similar maximum crack width where the first crack was initiated, specimens with longer fibres provided better widening resistance for cracks grown later and tended to have narrower crack width in overall.

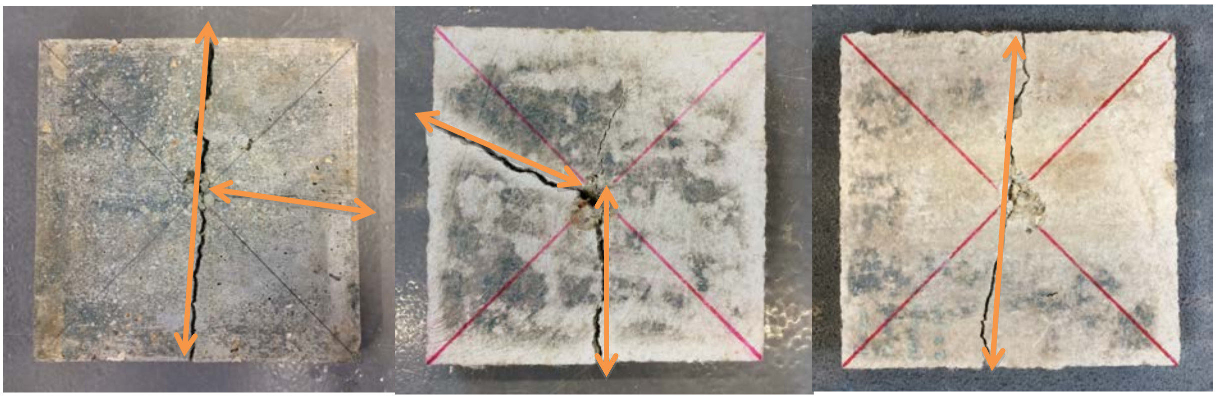

Figure 2 Failure pattern of HFRC panels with curing ages of 7, 14 and 28 days, respectively, from left to right

Impact blows. Number of blows required to initiate cracking and subsequently to cause ultimate failure is useful in determining overall pre- and post-cracking behaviour of HFRC panels under impact loading, which are presented in Table 2 in which the number of blows is the average from results of four panels with same testing parameters. It has been noticed that the average number of impacts to initiate cracking decreased with ageing, which could be explained again by better ductility of concrete panels at early ages. HFRC panels reinforced with 20 mm-long fibres required on average 5.75 blows at age of 7 days, 3.25 blows at age of 14 days and 2.5 blows at age of 28 days to initiate cracking. Almost similar results for HFRC panels with 10 mm-long fibres were also recorded. The similarity between the obtained results indicates that the improvement in pre-cracking behaviour of HFRC panels could be negligible. On the other hand, number of blows to cause ultimate failure varied between panels reinforced with different fibre lengths despite still decreasing with ageing. Panels reinforced with 20 mm-long fibres required on average 12 blows to cause failure while this is 10 for those reinforced with 10 mm-long fibres at 7 days. There is a similar trend at ages of 14 and 28 days as well, though it is less significant when compared to that at 7 days. In general, it means that after initiation of the first crack, specimens with fibre length of 20 mm provided better post cracking behaviour by arresting and bridging the cracks and subsequently required more number of impacts to cause ultimate failure.

Table 1 Compressive and flexural strength

	10 mm-long fibres			20 mm-long fibres		
	7 days	14 days	28 days	7 days	14 days	28 days
Compressive strength (MPa)	13.32	20.02	26.08	12.57	18.87	25.92
Splitting tensile strength (MPa)	2.04	2.96	3.80	2.43	3.10	4.08

Table 2 Impact test results (quantitative results)

	10 mm-long fibres			20 mm-long fibres		
	7 days	14 days	28 days	7 days	14 days	28 days
No. Of blows to initial cracking	5.25	3.25	2.75	5.75	3.25	2.5
No. Of blows to cause failure	10	6	4.75	12	6.75	5.25
Ultimate crack resistance R_u (in MPa)	6.99	3.67	2.48	9.56	5.03	2.77
Impact crack resistance ratio C_r	93.04	73.57	64.65	120.16	94.93	71.83
Energy absorbed at first impact	29.08	27.44	27.24	29.58	27.95	27.66
Energy absorbed at initiation of first crack	106.00	64.72	55.43	113.88	63.88	48.19
Energy absorbed at ultimate failure	223.14	105.73	72.90	275.49	125.04	86.41
I_{rs}	1.79	1.64	1.33	2.42	1.98	1.84
Residual impact load up to failure	292.46	167.25	140.72	337.14	181.11	151.31
Rate of energy absoprtion per impact load	0.76	0.63	0.52	0.82	0.69	0.57

Crack resistance ratio. Impact crack resistance ratio and the ultimate crack resistance of HFRC panels reinforced by 10 mm- and 20 mm-long hemp fibres at 7, 14 and 28 days are presented in Table 2. It can be seen that impact crack resistance ratios of specimens with 20 mm-long fibres are about 29% higher than that of those HFRC panels with 10 mm-long fibres, at both ages of 7 and 14 days. At the age of 28 days, same as the scenarios of 7 and 14 days, HFRC panels with longer fibres exhibited higher resistance to crack but just 11% higher compared to panels with shorter fibres. Therefore, it can be concluded that HFRC panels with longer fibres exhibited higher impact resistance at all ages, suggesting that longer fibres demonstrated better post-cracking behaviour, increasing the arresting and bridging of cracks. Obtained results also indicates that impact crack resistance ratio of HFRC panels are significantly reduced by ageing for both cases of 10 mm- and 20 mm-long fibres. For HFRC panels reinforced with 20 mm-long fibres C_r value decreased from

120.16 to 94.93 and further to 71.83 at ages of 7, 14 and 28 days, respectively. This trend shows that HFRC panels are more ductile at early ages and becomes more brittle by ageing.
Overall, longer fibres are more effective in inhibiting the growth of micro-cracks and blunting the propagation of these cracks before they joined up and formed macro-cracks. Therefore, more blows and consequently higher energy required to cause ultimate failure of panels reinforced with longer fibres. Also it has been evident that impact crack resistance ratio decrease by ageing of HFRCs as they become more brittle, which could be explained by the presence of higher level of moisture within specimens at early ages, caused by slow hydration process at early stages of hydration of cement matrix.

Energy absorption characteristics. Energy absorbed at first impact, up to initiation of the first crack and up to ultimate failure of HFRC panels are also presented in Table 2. It can be seen that HFRC panels with longer fibres and at younger age absorbed more energy at first impact. However, the difference was marginal. Moreover, there was a negligible difference in energy absorption of HFRC panels at initiation of the first crack for both 10 mm and 20 mm-long fibre specimens at all ages. However, HFRC panels tended to absorb less energy by aging to cause the first crack as they became less ductile. Based on the results of the present study, cumulative energy absorbed by a HFRC panel during each blow until failure was used for comparison. The corresponding values for energy absorbed up to ultimate failure of HFRC panels are also presented in Table 2. Comparing HFRC panels with 10 mm and 20 mm-long fibres, it can be seen that those with longer fibres (i.e. 20 mm) required 23%, 19% and 19% more energy to cause ultimate failure at ages of 7, 14 and 28 days, respectively, suggesting that longer fibres enhance post-cracking behavior by arresting and bridging cracks and subsequently require more energy to cause ultimate failure. Moreover, energy absorption up to ultimate failure of HFRC panels decreased with the increase in curing age. For instance, at 7 days HFRC panels reinforced with 10 mm-long hemp fibres absorbed 206% and 45% more energy that that at 14 and 28 days, respectively at ultimate failure. These numbers turned into 219% and 45% in case of 20 mm-long fibres. In general, it can be concluded that results obtained from number of blows, impact crack resistance ratio and energy absorption follow the same trend as they are all related with energy that require to cause ultimate failure of a HFRC panel under impact.
Energy absorption per impact load. Furthermore, impact load applied on HFRC panels at each blow was determined, so their cumulative addition up to failure can be considered in comparison of their respective energy absorption up to failure. This is due to the fact that higher impact load (caused due to minor errors occurring during manually operation of test) cause higher level of energy absorption in HFRC panels. Therefore, rate of energy absorption per impact load, presented in Table 2, is employed to consider the effect of inconstant impact loading. In general, rate of energy absorption per impact load followed the same trend as energy absorbed up to ultimate failure. However, it can be said that in general there is a smaller gap in enhancement of energy absorption of HFRC panels to that of found by absorbed energy. For instance, based on results obtained for energy absorbed, when comparing HFRC panels with 10 mm- and 20 mm-long fibres, those with longer fibres require 23%, 19% and 19% more energy to cause ultimate failure at the ages of 7, 14 and 28 days, respectively. However, these values can be reduced to 7.9%, 9.5% and 9.6% when considering impact load by employing rate of energy absorption per impact load. Therefore, as a result it can be concluded that HFRC panels with 20 mm-long fibres were subjected to greater impact load per blow compared to those of with 10 mm-long fibres.
Impact durability. Effect of fibre bridging determines the post-crack impact energy absorption and hence the impact ductility of concrete. Residual impact strength ratio for HFRC panels with different fibre lengths and curing age presented in Table 2 provides a good indication of post-crack behaviour of HFRCs after initiation of first crack. Results indicate that residual impact strength ratio increased by inclusion of longer fibres (20mm) within concrete and decreased with increase in curing age of HFRC panels. It means that post crack behaviour of HFRC panels enhanced with longer fibres and development of micro-cracks to macro-cracks was restricted. The longer the fibre

the greater the energy required to pull the fibre through the matrix, after the fibre to matrix bond is broken and the greater the contribution to the dissipation of energy contained in the advancing crack. It can be seen that I_{rs} of HFRC panels with 20 mm-long fibres are 35%, 21% and 38% greater at ages of 7, 14 and 28 days, respectively, when comparing to those with 10 mm-long fibres. Also, HFRC panels with 10 mm-long fibresat the age of 7 days have high value of I_{rs}, 9% and 35% higher than those with curing age of 14 and 28 days. With similar trend, HFRC panels with 20 mm-long fibres at age of 7 days have high value of I_{rs}, 22% and 32% higher than those with curing age of 14 and 28 days. This means that HFRC panels are more ductile at early ages.

Conclusions

Within the framework of this study, effects of fibre length on impact resistance of hemp fibre-reinforced concretes were investigated in order to determine the optimum fibre length. The following conclusions can be drawn:

- Fibre length affected splitting tensile strength of HFRCs with longer fibres leading to higher strength;
- Number of blows to cause ultimate failure is higher for HFRC panels reinforced with 20mm-long fibres than those with 10mm-long fibres;
- HFRC panels with longer fibre length provided better resistance to propagation of cracks at all ages;
- HFRC panels reinforced with longer fibres required more energy to cause ultimate failure and provided better resistance to crack propagation at all ages;
- Rate of energy absorption per impact load followed the same trend as energy absorbed up to ultimate failure but determined smaller gap in enhancement of energy absorption of HFRC panels to that of found by absorbed energy;
- Post-crack behaviour of HFRC panels reinforced with longer fibres was superior to that of HFRC panels reinforced with short fibres. With longer fibres, development of micro-cracks to macro-cracks was restricted and impact durability enhanced;
- Number of impacts to initiate cracking and cause ultimate failure, impact crack resistance ratio, energy absorption, and residual impact strength ratio all decreased with the ageing of HFRC panels as they became more brittle and less ductile; and
- Overall, longer fibres are more effective in inhibiting the growth of micro-cracks and blunting the propagation of these cracks before they joined up to form macro-cracks. Therefore, more blow and consequently higher energy required causing ultimate failure of panels reinforced with longer fibres.

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