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A NEW METHOD FOR IMPACT PROPERTIES
MEASUREMENT OF NATURAL FIBRE-REINFORCED
CEMENT COMPOSITES

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ABSTRACT

For safety reasons, the need for civil or military structures to sustain harsh impact loads has been emphasized more and more recently, and fibre-reinforced composite materials have an advantage. In this study, impact crack properties of coir fibereinforced cementitious composite (CFRCC) materials were investigated using a modified Charpy impact machine for penetrated impact loading. The impact deceleration was measured with a commercially available ceramic shear ICP® accelerometer; the temperature of the CFRCC specimen, broken surface during impact tests was determined using a high-speed thermal camera, and the acoustic emission during the impact moment was also recorded. Coupling with dispersants, defoamer and wetting agents, the impact resistant energy of CFRCC samples was improved by 1.44%, 5.33% and 20.88% after ageing for 7, 28, and 180 days, respectively. Thermal emissivity in the fracture surface of the CFRCC was significantly lower than with the conventional mortar. Results of acoustic noise during the breaking of the composites also showed that CFRCC could absorb more energy before it failed completely, leading to lower sound energy emission for CFRCC than for conventional mortar.
KEYWORDS
Charpy impact test, fibre-reinforced cement composite, impact behaviour, thermal properties, acoustic emission.

INTRODUCTION

The behaviour of cementitious composite materials under impact loading is of special concern in the research of safety requirements for civil or military structures in a harsh situation such as an earthquake, accidental impact or explosion. (Zhao 1998). The early experimental data of fibre reinforced cement composites (FRCC) showed a great improvement in impact strength and impact energy absorption. (Canche-Escamilla et al. 2002; Ramaswamy et al. 1983; Siddique 1993; Uzomaka 1976) compared to a pure cement matrix. Most of the dynamic loading tests for the FRCC materials used the drop-weight impact test method. This test is designed to obtain the relative performance of plain and fibre-reinforced composites containing different types and volume fractions of fibres (Balaguru and Shah 1992). It cannot, however, be used to quantitatively determine the impact properties of composites such as cracking velocity, surface temperature, and impact noise etc.

The traditional Charpy machine can provide powerful impact energy and by attaching an accelerometer set with PC support, the impact energy can be recorded as a high sensitivity impact signal. (Zhao 1998). These signals can be transferred to curves of crack velocity versus impact duration time. The crack velocity versus time relationship is superior to the traditional impact stress-strain curves in material characterisation. The measured stress-strain curves were never true value because at the instant of impact, when the front side of the specimen was hit by hammer, the other side (where the sensor lay) still remained stationary until the impact wave went through the specimen. (Zhao 1998).

Applying this modified Charpy system to concrete-like materials brings another interesting dimension to cementitious materials impact properties research. The whole barrier energy of impact tup was not absorbed totally by the sample. Most of the initial energy was changed to absorbed striking energy by the sample, one part of it remained in the impact tup as transferred to kinetic energy after impact, and the other impact energy was transferred to heat and sound during the impact moment. These surface temperature and fracture noise properties are also very important to composite materials.

The impact sustentation performance is one of the essential properties and even a critical
property under some conditions (earthquake, bomb attack, etc.) for structural components. FRCC has a high impact-resistance, (Banthia et al. 1993; Bindiganavile et al. 2002; Siddique 1993). However, there are no determined data to quantify their superior impact-resistant properties, including thermal and acoustic behaviors during fracture time. Such data is presented in this study and the performance of different CFRCC samples is discussed.

EXPERIMENTAL PROGRAM

Materials

Fibretex Pty Limited in Australia supplied coir fibre mat. Muntzing Chemie GMBH Company in Germany supplied the Agitan®, P800, and Dow Chemical Company in Australia provided the Methocel® A15LV. The Albatex® FFC was supplied by Ciba Specialty Chemicals Pty Ltd., Australia.

Composites Preparation

The coir fibre was cut to 2 cm then pre-dried in the oven under 80 °C for 10 hours before mixing. The experimental mixture design is shown in Table 1. All percentage values in the table are weight based, and the fibre content was 1.5% in all groups except R0 samples, which were plain mortars.

<table>
<thead>
<tr>
<th>Reference No.</th>
<th>Dispersant A15LV (%)</th>
<th>Defoamer P805 (%)</th>
<th>Wetting Agent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0</td>
<td>0.60</td>
<td>0.30</td>
<td>0.2</td>
</tr>
<tr>
<td>M1</td>
<td>0.60</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>M2</td>
<td>0.60</td>
<td></td>
<td>0.3</td>
</tr>
<tr>
<td>M3</td>
<td>0.60</td>
<td></td>
<td>0.2</td>
</tr>
</tbody>
</table>

The specimens were divided into two curing groups. One was normal water curing under 24 °C. The other was accelerated ageing method. For the accelerated ageing samples, the modified MacVicara’s accelerated ageing method (MacVicara et al. 1989) was used in the last two days of the curing period.

Testing Methodology

The Charpy impact test in this study used the impact energy of 300 J with an impact velocity $v_i$ of 5 m/s. The Charpy impact testing system is shown in Figure 1.
The ceramic shear ICP® accelerometer sensor stuck to the top of the hammer allows its impact deceleration signal to be recorded by a National Instruments DACCard connected to a lab laptop during the impact. The LabVIEW software was used to filter and process the data, and obtain the impact hammer deceleration versus impact duration time as shown in Figure 3.

Acoustic emission technique has been used as a tool for the non-destructive testing of structural materials since the 1980s (Akers and Garrett 1983; Meiser and Tressler 1982; Mobasher et al. 1990). The operating specification for MISTRAS 2001 acoustic emission equipment is shown in Table 2.

<table>
<thead>
<tr>
<th>System gain</th>
<th>Threshold</th>
<th>PDT</th>
<th>HDT</th>
<th>HLT</th>
<th>Signal filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 dB</td>
<td>45 dB</td>
<td>50 μs</td>
<td>1000 μs</td>
<td>1000 μs</td>
<td>10 kHz-1.2 MHz</td>
</tr>
</tbody>
</table>
**Calculations**

The velocity of the hammer (or the crack velocity of CFRCC) $v_i$ is estimated using Equation 1 with Newton's second law by integrating the deceleration signal recorded on the accelerometer sensor:

$$v_i = v_0 + \int_{T_0}^{T_1} a(t) dt \quad (t \leq T_1)$$

where $v_0$ stands for the original speed of the strike hammer ($v_0 = 5$ m/s in this paper), $v_i$ stands for the instant speed of the hammer when it is penetrating the specimen, $T_0$ and $T_1$ are the start and end time of impact as the hammer penetrates the specimen.

![Figure 2: Deceleration versus time curve in an impact test](image)

Figure 3 shows a schematic diagram of the hammer penetrating a specimen. The sample impact energy absorbed can be theoretically calculated using Equation 2 based on the energy conservation in the whole system:

$$E_i = E_s - M(v_i)^2 / 2 - m(v)^2 / 2 - E_H - E_u$$

where $E_i$ is the specimen's theoretical absorbed energy (for the water curing samples we used $E_w$, and for the accelerated ageing samples we used $E_a$), $E_s$ is the kinetic energy of the strike tup before impact, $m$ is the mass of the broken piece of the CFRCC specimen, which was detached when the hammer penetrated the specimen, $v$ is the velocity of the broken piece, $M$ is the mass of the strike hammer and frame.

![Figure 3: Schematic diagram of impact penetrating the CFRCC specimen](image)
$v_i$ is the velocity of the hammer leaving the specimen just after penetration, $E_H$ is the impact heat emission energy, and $E_S$ is the impact sound emission energy. As the comparative ratio of the broken piece mass $m$ (around 40 g) and the Charpy impact hammer system $M$ (25 kg) is so small, the kinetic energy of the CFRCC broken piece has been ignored in this calculation. Its heat and sound emission energies are also ignored for the same reason.

The theoretical absorbed energy has a relationship to the specimen's dimension. To remove this effect, the equivalent energy was used in this study and it was calculated by Equation 3.

$$E' = E_i / (L + H)$$

where $E'$ is the normalized absorbed impact energy and $E_i$ is the specimen’s theoretical absorbed energy (for the water curing samples we used $E'_w$, and for the accelerated ageing samples we used $E'_a$). $L$ is the sample thickness and $H$ is the actual height of the broken piece as shown in Figure 4. The equivalent impact energy has not been reported previously in the literature, so both the impact energy and the equivalent energy are described in this study to compare their relation to sample performance.

RESULTS AND DISCUSSION

Impact Crack Velocity and Absorbed Energy

Using Equation 1, the hammer velocity (discussed as sample crack velocity below) versus impact duration time can be calculated and plotted out. They are quite similar. For illustration propose, the plots of 28 days CFRCC specimens (M2) are shown in Figure 4. The Charpy impact system provides accurate dynamic crack velocity measurements based on the deceleration of the impact hammer.

It can be seen from Figure 4 that the impact crack velocity versus duration time curves are quite similar. The impact resistant behaviours of pure mortar and CFRCC samples are demonstrated clearly in the curves. For the same strike energy (25 kg hammer with 300 J energy), the CFRCC specimen can slow down the hammer quicker in the same impact duration time than pure mortar, indicating the water cured CFRCC absorbed more energy than mortar.

Results of the impact energy absorption in 7, 28 and 180 day aged samples are given in Figures 5 to 7, where the results of equivalent energy are listed together for comparison purposes. The left Y axis is for impact energy which was not considered a dimension factor (results shown in vertical bars), and the right Y axis is for the equivalent energy
which was normalised by the specimen's dimensional aspects (results shown in line and spatters) as expressed in Equation 3.

![Graph showing impact velocity vs. impact duration time]

**Figure 4** Impact velocity vs. impact duration time

- **Aged CFRCC**
- **Water Cure CFRCC**
- **Pure Mortar**

The impact behaviour of CFRCC highlights several interesting features. First of all, the specimen's dimension was an important factor influencing the samples' impact properties. A slight difference could be observed in all three Figures between the trend of the vertical bar (impact energy) and the trend of the line with spatters (equivalent energy). The latter curves show sample properties in a more reasonable way as the specimens were compared under the same conditions (normalized dimension).

Secondly, the impact properties of CFRCC are sensitive to the chemical agents (dispersant agent, defoamer and wetting agent) which cause result variations among M1 to M3. From Figures 5 to 7, the composite coupled with dispersant and defoamer agents (speci-
men M1) had a good energy absorption in 7 days ageing, however this combined effect was weakened with age. M2 samples gained higher and higher equivalent energy absorption than the other two from 28 days to 180 days ageing. Therefore, the addition of dispersant agent enhanced the interaction of fibre and matrix, and the introduction of defoamer agents into composites decreased the general impact toughness. The reason for this has been discussed in detail elsewhere. (Li et al. 2004).

![Figure 6: Impact energy results of 28 days aged samples](image)

![Figure 7: Impact energy results of 180 days aged samples](image)

Thirdly, as a matter of fact, the accelerated ageing method was applied in a different way between CFRCC and plain mortar or concrete. The ageing characterization of fibre and cement matrix has a large divergence which led to the incorrect ageing prediction results of 7 days aged samples (dash line in Figure 5) compared with the 180 days cured samples (solid line in Figure 7). The prediction results (represented by accelerated ageing meth-
od) in Figure 6 match very well with the results in Figure 7. A conclusion can be drawn that as to CFRCC (or other natural fibre reinforced composites), the recommended sample age for applying accelerated ageing method in CFRCC is 28 days. Though the ageing results in 180 days aged specimens still need to be further investigated, they are close enough compared with the trend of 28 days aged samples and 180 water cured ones.

The last significant point is the impact resistant improvement of CFRCC, evaluated against mortar. Only the M2 sample was chosen and investigated here. In 7 days ageing, the impact energy was improved by 1.44%, the equivalent energy was improved by 8.60% (ageing results were omitted), in 28 days, they were 1.10%, 5.80% respectively. The ageing impact energy and ageing equivalent energy were improved by 9.20% and 33.70% respectively; In 180 days, those figures were 20.88% and 16.60%, and the ageing impact energy and ageing equivalent energy were increased by 20% and 18.55%.

**Impact Thermal Emission**

During the impact loading period, a great amount of the deformation energy was transformed into heat energy dispersed inside and around the composites. However, there has been little research carried out in the cementitious composites field. A difference of 20.9% in fracture temperatures between the pure matrix and the CFRCC was measured in this study.

The thermal conductivity (λ) is a measure of the power insulat of the material; the λ of the cement matrix is around 1.28 W/m°C and the λ of our fibres is only 0.035 W/m°C (Bentchikou et al. 2004) which is extremely low compared to pure mortar. Based on Bentchikou’s thermal conductivity versus fibre content curves (Bentchikou et al. 2004), the thermal conductivity of 1.5% fibre content CFRCC should be around 0.5 W/m°C. The fracture temperature result of samples during the impact shown in Figure 8 agrees well with the estimated value, indicating the CFRCC transferred less heat than pure mortar during impact.

Figure 8 also shows that the fracture temperature of the water cured CFRCC samples rose gradually and the maximum peak temperature was 32°C. The temperature of aged CFRCC rose fairly sharply and reached the peak at 51°C. The pure mortar sample had the quickest temperature rise and its highest temperature peak was 62°C. CFRCC materials have an excellent nature in low thermal conductivity and good thermal capacity to store the generated heat during impact. These superior heat insulation performances will be weakened as time passes. Even so, the aged samples still functioned better in heat insulation than the pure mortar.
The images from the thermal high-speed camera are presented in Figures 9-11. The temperature within the figures is nearly the one in about 100 ms referred to Figure 8. In Figure 9, it shows that at the moment the pure mortar specimen was penetrated by the shock hammer, lots of the hot dust and tiny particles were driven out of the test specimen. In the situation of the CFRCC specimen (Figure 10), the temperature did not change a lot between the beginning moment and during impact penetrated. When we compare these three specimens at impact finish moment, the plain mortar (Figure 9) was undoubtedly smashed and had lost its original shape; the accelerated ageing CFRCC specimen (Figure 11) still retained its shape, but there were some large visible cracks, which meant the material was actually disintegrating; only in the 28-day normal curing CFRCC specimen (Figure 10) did the material still hold its shape after penetration. This suggests that the superior heat conduction property of CFRCC will be weakened as the materials become tougher and tougher. The thermal images in Figures 9-11 indicate that the aged CFRCC has a better impact resistance than the plain mortar and will not be broken totally under intense impact loading. Post-examination of the impacted specimens confirmed the findings.
Impact Acoustic Emission

When a material begins to fail due to bending, cracking, or tensioning, the stresses inside the material will be redistributed and rise to stress waves which are propagated within the material. When these stress waves reach the surface they can be detected by utilizing a sensor which converts the energy received from the stress wave into an electrical impulse. This procedure is known as an acoustic emission measurement (Akers and Garrett 1983).

Figure 12: The acoustic emission versus impact time of 28 days CFRCC and mortar.

Figure 12 shows the curves of acoustic emission versus time of 28 days age mortar and CFRCC for interval counting (1 μs) (where peaks represent the number of emissions above a pre-set threshold counted within a specific time interval). Because of different record devices used, there were some slightly different duration time between Figures 4, 8 and 12. These results show that initial micro-cracking can be detected almost immediate-
ly after the impact is applied in the specimens. This suggests that acoustic emission can be a useful method for characterising the development of pre-crack in CFRCC materials together with the Charpy impact test. From Figure 12, it can be seen that the plain mortar created 5 times more acoustic emission compared to the CFRCC sample as the hammer struck. Though the aged CFRCC was getting tougher, its acoustic emission is still just 1/3 of the plain mortar.

Therefore, the coir fibre inside the CFRCC could delay the impact penetration procedure and absorb most of the acoustic emission generated by stress waves.

**CONCLUSION**

Based on this study, the following can be concluded:

With 0.6% dispersant agent and 0.3% wetting agent, the coir-fibre-reinforced cementitious composite (CFRCC) can absorb more impact energy than conventional mortar. After 7 days, ageing the energy absorption was improved by 1.44%, and the equivalent energy was improved by 3.60%; after 28 days, they were 1.10% and 5.80%, respectively. The ageing impact energy and ageing equivalent energy were improved by 8.20% and 35.70% respectively. After 180 ageing days, the figures were 20.88% and 15.60%, and the ageing impact energy and ageing equivalent energy were increased by 20% and 18.55%.

The CFRCC has a lower maximum fracture temperature, a smaller acoustic emission during failure and is less brittle under strong impact penetration compared to the conventional mortar. Though the accelerated aged samples show that these functions were weakened as the ageing time increased, the performance of aged CFRCC samples is still much better than the plain matrix. CFRCC is therefore a better material for structures subjected to impact loading and where the heat insulation and soundproofing are important issues.

The combination of these three different measurements (modified Charpy test, thermal analysis and acoustic emission monitoring) gives full information on the characteristics of the CFRCC materials. The kinetic energy absorption, thermal behaviour and acoustic emission energy together form a whole picture of energy transfer during the impact moment. Such combined measurements can be applied conveniently in cementitious composites materials research.
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REFERENCES


