Blast Response of Hybrid-Fibre Engineered Cementitious Composite (ECC) Panels

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This research originally aimed to expand the knowledge of ECC behaviour when subject to blast loading. Some research has been conducted with mono-fibre ECCs but there is currently no research on the behaviour hybrid-fibre ECCs subject to blast loading. The aim was modified to subject ECC panels with 1.75%PVA and 0.58%SE fibres, designed to have both good energy absorption and strength characteristics, to high-velocity gas-propelled projectiles, designed to mimic blast loading. The resulting damage will be compared to FRC and HSSRC panels in order to determine if the ECC mix is superior. The data gained from the experiment will also be collected in order for further research to be conducted on a numerical prediction model for the ECC.

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Nomenclature

ECC = Engineered Cementitious Composite
FRC = Fibre Reinforced Concrete
SFRC = Steel Fibre Reinforced Concrete
PVA = Polyvinyl Alcohol
PE = Polyethylene
PO = Polyolefin
PP = Polypropylene
SE = Steel
HSSRC = High Strength Steel Reinforced Concrete

1 OCDT, School of Engineering & Information Technology. ZEIT4500.
I. Introduction

Cement based materials are often used for blast and impact proof structures, both for defence and civil purposes. They are favourable because their density gives good resistance to both blast and impact. High strength steel reinforced concrete (HSSRC) has been used to build blast resistant structures providing resistance through bulk volume. Using steel reinforced concrete for blast resistance is uneconomical as it relies on the weight of the concrete to absorb the energy of the blast which requires the use of large volumes of concrete in order to effectively resist blast loading.

The environmental impact of producing excess amounts of cement should also be considered as the process used to produce cement also results in large amounts of CO₂ to be released into the atmosphere. By developing new products and methods for building structures which use cement to make the material stronger means less cement is required and has a positive impact on the environment.

Fibre reinforced composites (FRC) composed of normal concrete with discrete short fibres distributed randomly throughout. FRC has improved tensile and flexural strength over normal concrete, as well as fracture toughness and improved resistance to fatigue and impact loading. This is an improvement on HSSRC as it uses the mechanical properties provided by the fibres to the advantage of the concrete strength. However, the addition of fibres to concrete does not improve the tensile strength of the FRC, nor does the strain capacity increase after the first crack in the matrix appears [1], meaning that once the matrix cracks, the concrete can’t take any more load. Due to these characteristics, the failure of FRCs is described as quasi-brittle and exhibits a tension-softening behaviour when it has reached its ultimate tensile stress.

Engineered cementitious composites (ECC) are a cement based material containing cement, fly ash, sand and water, reinforced with randomly distributed short discrete fibres. The fibre volume is usually less than 2% but slightly higher percentages have proved to maintain the desired mechanical properties [2] [3]. ECC’s exhibit improved mechanical properties over FRC’s with tensile strain-hardening behaviour, improved energy absorption and crack resistance due to its multiple-micro-cracking behaviour [1].

Figure 1 shows a schematic of the characteristics described. It shows normal concrete quickly losing its strength once a crack has formed after a small strain. The FRC is shown exhibiting the tension-softening behaviour, allowing further strain to occur after the first crack appears until the ultimate strain has been reached. The HPFRCC is shown exhibiting strain hardening behaviour because of its multiple cracking characteristic. The HPFRCC also exhibits tension softening behaviour once crack localisation occurs. It should also be noted that the tension at which the first crack appears is dependent upon the matrix material, hence why the three types of concrete are shown to yield at the same point.

Many types of fibres have been proposed and tested for use in ECCs including: steel (SE), polypropylene (PP), polyethylene (PE), polyolefin (PO), and polyvinyl alcohol (PVA). All of the mentioned fibres are used as they are likely to improve the strength or energy absorption of the cementitious material. Much of the research so far has focussed on adding only one type of fibre to the mix, known as mono-fibre composites. The addition of two or more types of fibres to a mix is known as a hybrid-fibre composite.

The reason for adding fibres to cementitious materials varies with the properties of the added fibre. High modulus fibres such as steel improve the tensile and flexural strength but compromise the energy absorption capacity because of low ductility. Conversely, low modulus fibres, such as PVA or PE fibres, result in a high
ultimate tensile strain because of the improved ductility they provide as well as the micro cracking behaviour, although they exhibit low ultimate strength because of the low strength of the fibres.

If a structure is to be blast resistant, it must possess a high ultimate strength as well as good ductility and ultimate strain. With these characteristics, a structure should be able to absorb energy from the blast without failing.

II. Literature Review

Little to no research has been conducted on hybrid-fibre ECC response to blast loading. There is, however, research on the impact response of mono-fibre ECCs and limited research on the impact response of hybrid-fibre ECCs. There is also some research on various other methods of improving cementitious material’s resistance to blast loading. By combining what has been learnt from all of these sources, it is possible to determine the parameters which should be used in this research and to make the research more relevant by making it comparable to the other research.

A. Fibre Compatibility

In order to resist damage from blast, a material needs to both be strong and flexible, allowing it to absorb the blast energy while sustaining little damage. It is almost impossible for a single fibre to provide both of these characteristics in the same cement matrix, leading to the use of a single fibre for each characteristic. Steel has a large Young’s Modulus, making it an excellent candidate to fulfil the strength requirement of the hybrid-fibre ECC. In order to allow a cement matrix to deflect with minimal damage, a fibre which has good strain capacity is required. Plastic fibres such as Polyolefin (PO), Polyvinyl Alcohol (PVA), Polypropylene (PP) and Polyethylene (PE) all have desired characteristics to fulfil the required role in the ECC. Previous research by Bell et al. has shown that the elastic modulus of the second fibre should be less than or equal to that of PVA, ruling out the use of PE. PVA was chosen as it is in the high range of allowed Young’s Modulus values as well as having good tensile strength. The addition of these two fibres into the ECC mix has proven to give the desired characteristics in previous tests by Bell, Kerr and Volant.

<table>
<thead>
<tr>
<th>Fibre</th>
<th>Tensile Strength (MPa)</th>
<th>Modulus of Elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyolefin (PO)</td>
<td>275</td>
<td>2.65</td>
</tr>
<tr>
<td>Polyvinyl Alcohol (PVA)</td>
<td>900</td>
<td>29</td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>445-480</td>
<td>5</td>
</tr>
<tr>
<td>Polyethylene (PE)</td>
<td>2610</td>
<td>66</td>
</tr>
<tr>
<td>Steel (St)</td>
<td>1275</td>
<td>200</td>
</tr>
</tbody>
</table>

B. Models of Failure

Three papers [1] [7] [8] have been found which describe theoretical equations and concepts that can be used to understand the failure mechanisms of fibre-reinforced composites under tensile and flexural loading. They largely describe the characteristic inelastic behaviour of fibre reinforced composites as a consequence of their crack bridging and micro cracking behaviour.

Fischer et al’s paper states that for fibre reinforced composites to effectively change the properties of the matrix material, the fibres in the cracked section must be able to carry the stress that was in the matrix prior to cracking. This provides a basis as to the percentage of fibres to be used and the material properties required of the fibres in order to improve the properties of the composite.

ECCs fail by firstly exhibiting small ‘micro cracks’, which occur throughout the matrix. These micro cracks allow the fibres to take the strain being delivered to the material, in this case utilising the characteristics of the PVA fibres. The numerous micro cracks then bridge together to form larger cracks which eventually leads to localisation and failure. By virtue of the micro cracking behaviour, the material is able to sustain more straining before failure and thus absorb more energy, an essential characteristic for blast resistance.

C. Mixing Technique

It is important that when mixing fibre reinforced composites, the fibres are evenly distributed. A paper by Zhou et al. [9] showed the importance of the mixing sequence in ensuring the even distribution of fibres and desired behaviour of ECCs. The paper develops a new mixing sequence where part of the required water is mixed with the cement paste, then the fibres are added, and finally the rest of the water. An experimental analysis of the tensile strength, ultimate strain and tensile stress, and the fibre distribution of the specimens mixed using the standard and new procedures were conducted. The results showed that the new mixing procedure improved the distribution of the fibres and also increased both the ultimate tensile stress and strain of the specimens.
This mixing procedure will be applied when mixing both the FRC and ECC specimens in the research to be conducted to ensure the optimum material properties of the composites.

D. Experiment Design

Many papers have been written about blast experiments conducted using various techniques for strengthening concrete. Many of the papers [10] [11] [12] [13] [14] use panels mounted vertically and set up in such a way that more than one specimen can be tested with a single charge. These experiments also have a standoff distance in the order of metres. This type of setup accurately resembles damage inflicted upon walls by the blast but because of the large standoff distance and cumbersome frames is not conducive to gaining data for numerical studies.

Two other papers [15] [16] testing concrete panels against blast loading have a similar experiment setup. Both experiments had a hole in the ground with a frame to rest the panels on, with the ground level with the panel. The charge was set above the panels and parameters measured from there. The standoff distances were still in the order of metres but this setup is closer to what can be achieved in this experiment.

A paper on numerical prediction of blast response of concrete slabs [17] also had a setup with the panels horizontal but was above the ground and restrained at the edges by a steel frame. The standoff distance for these panels was quite small, in the order of hundreds of millimetres, and was a numerical modelling paper. This paper provides a figure for the weight of charge that should be used and the required size of the panels to incorporate the whole blast affected zone to be used for this research.

E. Current Research

This research expands on research that has been conducted on the same topic endeavouring to produce an ECC which is capable of withstanding both high velocity impact and blast loading. Extensive research was conducted to produce an ECC with the optimum volume percentages of SE and PVA fibres.

An ECC mix with 0.75%SE and 1.25%PVA [18] was trialled against high velocity impact with better penetration resistance and energy absorption than another 1.5%PE, 0.5%SE ECC mix and a plain concrete mix. The paper recommended that the mix should be improved.

An improved ECC mix with 1.75%PVA and 0.58%SE fibres was then tested [2] [3] for material properties as well as its response to high velocity impact. The material properties for this mix showed promise with an ultimate flexural strength of 13.4MPa, tensile strength at first crack of 5.34MPa, ultimate tensile strength of 4.0MPa, and a flexural strain of 3.6%. The high velocity impact tests of the same mix also proved that it was superior to a different ECC mix and plain concrete.

The 1.75%PVA, 0.58%SE ECC mix will be used in this research due to the promising research conducted so far.

III. Rationale

This research is aimed at expanding the knowledge of hybrid-fibre ECC’s, particularly their response to blast loading. The mix designed tested in Soe, Zhang and Zhang’s papers [2] [3] showed good results in their high speed impact test and the material testing showed good results exhibiting the desired mechanical properties.

The key area of research was to test the suggestion that the 1.75% PVA and 0.58% SE hybrid-fibre mix was superior in its blast response over HSSRC and mono-fibre SFRC. The testing was not designed to replicate a scenario such as a car bomb exploding near a reinforced wall, but rather to compare the damage done to each of the three types of panel in order to determine if the ECC panel was superior in its resistance to the blast.

A secondary aim for the experiment was to provide data from the blast itself and blast response of the panels, particularly the ECC panel, such that a computer model for the ECC under blast loading could be constructed and a numerical model for the for the ECC under blast loading could be constructed and validated. The computer model will not be attempted in this research but it is appreciated that the experimental data that could be obtained is valuable for further research and the opportunity to collect such data should be exploited. Experimental data collected could include charge weight, standoff distance, blast pressure, panel deflection, as well as the material properties and dimensions of the panels.

IV. Methodology

Three types of panels are to be tested, giving a good comparison of the ECC panel against concrete mixes currently used for blast protected structures. The ECC panel will be compared with a high strength concrete, steel bar reinforced panel and a steel fibre reinforced high strength concrete panel. The concrete mix for the HSSRC and SFRC will be the same save for the reinforcement to give a good representation of the different blast response characteristics of the two types of reinforcement.

Zhou et al produced a paper [17] detailing a blast loading experiment conducted in order to compare the results with a numerical prediction. The setup they used is the basis for the setup of the experiment to be
conducted. The paper also proved value in determining how large the panels need to be in order to incorporate the whole blast affected zone and what size charge and standoff distance is appropriate for the experiment.

A. Panel Design

One research experiment [17] aimed at a numerical prediction of blast response of a concrete panel showed the blast affected zone and documented the charge types and weight. Using this data it was possible to determine appropriate dimensions for the panels and charge weights required to give comparable results.

The panels will be 700mm long, 700mm wide, and 75mm deep which should be large enough to incorporate the entire blast affected area of an approximately 0.5kg C4 charge at a 100mm standoff distance.

B. Mix Design

The ECC mix design will be the same as used by Soe, Zhang and Zhang in their 2 papers with 1.75% PVA and 0.58% SE by volume. The mix for the HSSRC and SFRC panels are based on the mix used in Soe et al’s paper for their grade N90 normal concrete. The same proportions will be used for the two mixes with the only variation between them being the difference in reinforcement types. There is a difference in the percentage of reinforcement present in each mix with the HSSRC at about 1.2% steel, the SFRC at 2% and the ECC at 2.33% fibres. Although it appears there is a bias towards the ECC with the amount of reinforcement each mix is provided, these percentages were chosen as they represent typical percentages used for the particular types of mixes.

Table 2: Mix designs by weight proportion

<table>
<thead>
<tr>
<th>Mix</th>
<th>Cement</th>
<th>Fly Ash</th>
<th>Coarse Aggregate</th>
<th>Sand</th>
<th>Water</th>
<th>HRWR</th>
<th>PVA</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECC</td>
<td>1.00</td>
<td>1.20</td>
<td>-</td>
<td>0.80</td>
<td>0.56</td>
<td>0.01</td>
<td>1.75</td>
<td>0.58</td>
</tr>
<tr>
<td>SFRC</td>
<td>1.00</td>
<td>0.11</td>
<td>2.34</td>
<td>1.75</td>
<td>0.38</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>HSSRC</td>
<td>1.00</td>
<td>0.11</td>
<td>2.34</td>
<td>1.75</td>
<td>0.38</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The steel fibres which will be used are 13mm long and 0.2mm in diameter cuppered micro steel fibres. The PVA fibres are 8mm long and 0.038mm in diameter, as shown in Fig 2.

Figure 2: ECC mix fibres. SE fibre [27] on left, PVA fibre [28] on right.

Due to volume restrictions on the concrete mixer used, it was necessary to mix each panel in a separate batch. This gave way for differences in mixes, some of which are evident in the compression testing results.
C. Material Testing

Material testing was comprised of compression testing cylinders of each mix. The cylinders were 100mm in diameter and 200mm in height and were made and cured in accordance with AS 1012.8.1-2000 [19]. Tests were conducted at 7, 14, and 28 days after casting to ensure the mix is similar to the one being replicated. Three cylinders were tested from each panel at 7 and 14 days, 2 cylinders from each panel were conducted at 28 days with 2 cylinders retained for testing at the time of the experiment. The 28 day compression results are shown below, along with a graph of the averaged compressive strengths at 7, 14 and 28 days.

Table 3: 28 Day Compressive Results

<table>
<thead>
<tr>
<th>Panel</th>
<th>ECC</th>
<th>SFRC</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56.85</td>
<td>73.62</td>
<td>79.41</td>
</tr>
<tr>
<td></td>
<td>59.65</td>
<td>74.00</td>
<td>75.10</td>
</tr>
<tr>
<td>avg</td>
<td>58.25</td>
<td>73.81</td>
<td>77.26</td>
</tr>
<tr>
<td>2</td>
<td>61.35</td>
<td>80.35</td>
<td>69.80</td>
</tr>
<tr>
<td></td>
<td>63.08</td>
<td>80.54</td>
<td>67.82</td>
</tr>
<tr>
<td>avg</td>
<td>62.22</td>
<td>80.45</td>
<td>68.81</td>
</tr>
<tr>
<td>3</td>
<td>60.34</td>
<td>56.44</td>
<td>73.71</td>
</tr>
<tr>
<td></td>
<td>60.76</td>
<td>55.06</td>
<td>72.07</td>
</tr>
<tr>
<td>avg</td>
<td>60.55</td>
<td>55.75</td>
<td>72.69</td>
</tr>
</tbody>
</table>

D. Experimental Testing

It was originally planned to conduct blast testing with military support at the Joint Proof and Experimental Unit (JPEU) in Graytown, Victoria. Due to a number of setbacks, it was decided to discontinue the pursuit of this particular experiment.

In order to still be able to test the panels, it has recently been decided to attempt to use a high velocity gas gun. A projectile with a flat surface will be used in the attempt to replicate the shock waves produced by an explosion, as well as a pointed projectile in order to compare the types of damage and failure caused by the different types of projectile.

It is hoped that a velocity of 150ms\(^{-1}\) can be achieved from the 127mm (outside diameter) gas gun using a 120mm diameter projectile with an approximate mass of 0.5kg. These parameters should produce the desired effects on the panels to give a comparison of their energy absorption capacities.
Figure 4 shows the specifications of the proposed projectiles to be used in the experiment. The combined mass of the sabot and projectile will be approximately 0.5kg in order to gain the required velocity. The sabot will be made of a lightweight wooden or plastic material in order to allow the tool steel projectile to be as large as possible within the 0.5kg limit.

V. Expected Outcomes

It is expected, as previous research on this material [20] [21] shows, that the ECC will show improved resistance to the impact. The previous research showed that the ECC panels had a smaller entry hole and minimal spalling on the reverse side. This is by virtue of its superior strength and strain capacity.

The SFRC is expected to have good resistance to spalling on the front side of the panel, due to its good strength obtained from the steel fibres, but spalling on the reverse side, due to the lack of strain resistance.

Because of its brittle nature, the HSSRC has shown to have spalling on both the front and reverse sides of the panel. This would lead to a quick drop in strength and possible failure of the panel when used in a structure.

The performance of each panel will be judged both visually and by measurement of the depth and diameter of spalling on both the impact and reverse sides.
References


