FIBRE REINFORCED ULTRA HIGH PERFORMANCE CONCRETE UNDER IMPACT LOAD

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Keywords: UHPC, impact resistance, steel fibres.

Summary: The impact resistance of ultra high strength concrete as an alternative material for driven piles was investigated by subjecting concrete cylinders to series of impacts. The type and amount of steel fibres and concrete composition were varied. Impact resistance was characterized by the number of impacts applied before the ultrasonic pulse velocity decreased by 10%. The results show that the impact resistance of ultra high strength concrete is mainly determined by the type and amount of steel fibres rather than binder composition. Volumetric replacement of micro steel fibres by larger fibres (straight and crimped) resulted in loss of impact resistance.

1 INTRODUCTION

At present the ground for construction is improved using steel pipes for the production of driven piles [1]. However, the price of steel is subject to considerable variation. Moreover, large amounts of energy are required for the production of steel construction components. Alternative materials for the production of driven piles are therefore both economically and ecologically desirable. This is a possible application for ultra high strength concrete (UHPC), but would require ductile material behaviour or slow crack development to withstand impact during pile driving. Such properties may be obtained by adding steel fibres. Between 1.5 and 3.0 vol.% micro steel fibres up to 0.20 mm in diameter are usually added to contemporary ultra high strength concrete mixes [2, 3]. However, owing to the manufacture process, reinforcement with such very fine steel fibres is expensive and has a significant environmental impact. Consequently, replacement of the micro steel fibres by fibres with a significantly larger diameter would have a favourable effect.

In the present investigations, the impact resistance of cylindrical concrete specimens reinforced with up to 3 vol.% micro steel fibres was firstly characterized by a specially developed laboratory procedure. Part of the micro steel fibre content was replaced by fibres with a larger diameter in the subsequent investigations. In addition, the effect of concrete composition on impact strength was considered by varying the type of addition and reducing the Portland cement content of a mix.

2 DRIVEN PILES IN SPECIALIST FOUNDATION ENGINEERING

Pipe piles are usually driven into the ground with an excavator equipped with a hydraulic hammer, Fig. 1. The individual pipe sections are up to 6 m in length with an external diameter between 118 and 170 mm and a wall thickness between 7.5 and 13.0 mm. Once a pipe length has been driven completely into the ground, the next length is fitted using a sleeve coupling and pile driving continued until a layer of ground is produced which is capable of sustaining a load [4].
Piles may be constructed in two ways. By filling the pipe with concrete after driving, piles are produced which transfer the load of the later construction via peak pressure. Frictional piles are another possibility. In this case, an injecting device at the pipe head injects concrete continuously into the pipe during driving until the concrete emerges at the bottom of the pile and rises up outside the pipe [4].

3 EXPERIMENTAL PROCEDURE

3.1 Concretes, Production and Specimens

Table 1 shows the composition of the UHPC investigated. Based on concrete C0 made without steel fibres, concretes C1 to C6 were produced to investigate the effect of the amount and type of steel fibres. Concretes C0 to C5 were made with a well cement of strength class 42.5 N. Silica fume and quartz sand with mean particle sizes of 0.15 µm and 0.3 mm, respectively, were used in the mixes. Concretes C0 to C4 contained quartz flour which was volumetrically replaced by ground limestone in C5. The composition of concrete C6 was very different from the other concretes. A Portland cement of strength class 42.5 R for underground construction was also used, but substantially replaced with ground granulated blast-furnace slag (GGBS) and ground limestone.

As well as the effect of micro steel fibres Ø = 0.16 mm alone in concretes C1 and C2, the effect of a fibre mixture was investigated using micro steel fibres together with steel fibres Ø = 0.4 mm and crimped steel fibres Ø = 0.5 mm. The fibre content of the concretes ranged from 0 vol.% in C0 to 3.0 vol.% in concretes C2 and C4. A superplasticizer based on polycarboxylate ether was used to fluidify the mixes.

The concretes were produced in an intensive mixer to obtain a high degree of homogenisation of the fresh concrete. After mixing the dry materials with the steel fibres, the water was added with 40% of the superplasticizer. The remaining superplasticizer was added after mixing for 2 minutes. The mixing time after water addition was 3.5 min.
### Table 1: Composition of the UHPC

<table>
<thead>
<tr>
<th>Materials</th>
<th>C0</th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>C4</th>
<th>C5</th>
<th>C6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>680</td>
<td>680</td>
<td>675</td>
<td>680</td>
<td>675</td>
<td>657</td>
<td>212</td>
</tr>
<tr>
<td>Silica fume</td>
<td>138</td>
<td>138</td>
<td>138</td>
<td>138</td>
<td>133</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Quartz flour</td>
<td>360</td>
<td>360</td>
<td>356</td>
<td>360</td>
<td>356</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ground limestone</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>359</td>
<td>468</td>
</tr>
<tr>
<td>GGBS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>338</td>
</tr>
<tr>
<td>Quartz sand</td>
<td>990</td>
<td>990</td>
<td>982</td>
<td>990</td>
<td>982</td>
<td>956</td>
<td>957</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>21</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>Water</td>
<td>179</td>
<td>179</td>
<td>170</td>
<td>179</td>
<td>170</td>
<td>165</td>
<td>179</td>
</tr>
<tr>
<td>Micro steel fibres 0.16×6 mm</td>
<td>-</td>
<td>118</td>
<td>236</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>Steel fibres 0.4×10 mm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>39</td>
<td>98</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>Steel fibres crimped 0.5×6 mm</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>39</td>
<td>98</td>
<td>39</td>
<td>39</td>
</tr>
<tr>
<td>Steel fibre content Vol.-%</td>
<td>0</td>
<td>1.5</td>
<td>3.0</td>
<td>1.5</td>
<td>3.0</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>w/b&lt;sup&gt;1)&lt;/sup&gt;</td>
<td>-</td>
<td>0.24</td>
<td>0.24</td>
<td>0.24</td>
<td>0.24</td>
<td>0.24</td>
<td>0.61</td>
</tr>
</tbody>
</table>

| Compressive strength<sup>2)</sup> | MPa | 215 | 218 | 233 | 222 | 213 | 210 | 155 |

<sup>1)</sup> including silica fume and water content of the superplasticizer  
<sup>2)</sup> determined using cylinders H/Ø=50/50 mm

Cylindrical concrete specimens with dimensions H/Ø=200/100 mm corresponding to the geometry of the piles were chosen for the laboratory investigations. Six cylinders were made for each mix. The cylindrical moulds were filled in the vertical position. No additional compaction was performed. The cylinders were demoulded after 24 h and stored up to an age of five days in a climate chamber at 20°C and 65% RH. The specimens were then heat treated for 48 h immersed in water at 90°C. Finally, the cylinder ends were ground parallel to a height of 200±1 mm and the specimens stored at 20°C and 65% RH until testing.

#### 3.2 Characterization of Impact Resistance

An impact device was used to test the impact resistance of the concretes, Fig.2.

![Impact resistance testing device](image)

**Fig. 2:** Impact resistance testing device with specimen according to DIN EN 1097-2 [5]
Each specimen was placed in the centre of an anvil during testing. Guided by a rail, a weight of 50 kg fell from a height of 600 mm onto a die positioned at the top of the specimen. The specimen was loaded with 1000 N before testing.

After a series of five consecutive impacts each specimen was removed from the device and the ultrasonic pulse velocity measured between the ends of the cylinder, i.e. in the direction of impact [6]. Transversal point-contact transducers were used and five individual measurements were performed for averaging, Fig. 3. The cylinder was replaced in the testing device and the procedure repeated.

![Specimen with paths for ultrasonic velocity](image)

In order to assess the impact resistance of the specimens, an impact failure number was defined as the number of impacts required to reduce the ultrasonic pulse velocity by 10% with respect to the initial value. It also characterizes the impact resistance of the concretes.

4 RESULTS AND DISCUSSION

4.1 Effect of Micro Steel Fibre Content on Impact Resistance of the UHPC

Fig. 4 shows the impact failure numbers determined for the concretes C0, C1 and C2 reinforced with micro steel fibres.

In contrast to concrete C0 with an impact failure number of four, the use of 1.5 and 3.0 vol.% micro steel fibres in concretes C1 and C2 increased the mean impact failure number to 41 and 98, respectively. In an earlier publication [7], this increase was explained by the higher number of fibres in the specimens and the higher degree of horizontal orientation of the fibres. The impact resistance is increased by the slower crack propagation.

The scatter in impact resistance failure number within a series of cylinders was relatively large, Fig. 4. The most pronounced scatter occurred for the cylinder in series C2. As well as the test method itself, this was also due to a high degree of fibre sedimentation in the fresh concrete, see [7].
Fig. 4: Effect of micro steel fibre content on the impact failure number

A cylinder after impact testing to the failure criterion showing the typical appearance of the damage is shown in Fig. 5.

Fig. 5: Typical appearance of damage in a cylinder after impact testing to failure

As expected, mainly longitudinal cracks formed during testing. This indicates tensile loading perpendicular to the direction of impact. Horizontal cracks occurred only occasionally. In addition to the cracks, spalling was noted to be most pronounced at the base of the specimens.

4.2 Effect of the Type of Steel Fibres

Concretes C3 and C4 were used to investigate the extent to which impact resistance changes when micro steel fibres are partially replaced by ecologically and economically favourable fibres with a larger diameter. In contrast to concrete C1 with 1.5 vol.% micro steel fibres, concrete C3 contained the same volume of fibres, but with more larger fibres: 0.5 vol.% micro steel fibres, 0.5 vol.% straight steel fibres $\Phi = 0.4$ mm and 0.5 vol.% crimped steel fibres $\Phi = 0.5$ mm. In the case of concrete C4, the fibre content was increased to a total of 3 vol.% by adding more of the larger fibres: 0.5 vol.% micro steel fibres, 1.25 vol.% straight steel fibres and 1.25 vol.% crimped steel fibres. Concretes C3 and C4 contained at 0.5 vol.% the same amount of micro steel fibres.
In Fig. 6 the impact failure numbers (with scatter) determined for concretes C3 and C4 are compared with the values for the concretes C1 and C2 reinforce with micro steel fibres alone.

The impact failure number of concrete C3 with 1.5 vol.% mixed fibres was 25. On average, 41 impacts led to failure of concrete C4 with 3.0 vol.% mixed fibres. This impact failure number corresponds to that of a concrete with 1.5 vol.% micro steel fibres (C1 in Fig. 6), i.e. as well as 0.5 vol.% micro steel fibres, 1.25 vol.% straight steel fibres (Ø = 0.4 mm) and 1.25 vol.% crimped steel fibres (Ø = 0.5 mm) must be added to achieve the impact resistance level of the cylinder reinforced with 1.5 vol.% micro steel fibres alone. The mean impact failure number of concrete C4 with a mixture of steel fibres was only about half that of the concrete C2 reinforced with the micro steel fibres, although the total fibre volume was the same (3.0 vol.%).

The results show that volumetric replacement of part of the micro steel fibre content with larger fibres led to lower impact failure numbers and therefore loss of impact resistance.

### 4.3 Effect of Concrete Composition

The effect of concrete composition was also investigated using the same fibre mixture (three different steel fibres) and fibre content (1.5 vol.%). Firstly, the quartz flour in mix C3 was replaced by finely ground limestone (C5). Mix C6 was used to investigate the effect of a large reduction in Portland cement content due to replacement with GGBS and ground limestone on the impact failure number of the concrete. The impact failure numbers determined for the concretes are shown in Fig. 7.

The impact failure number was reduced slightly from 25 (C3) to 18 (C5) by the replacement of quartz flour by ground limestone. A further reduction was not produced by the use of GGBS and ground limestone (C6) instead of a large amount of Portland cement.
5 CONCLUSIONS

An impact test is presented which was used to investigate the impact resistance of ultra high strength concrete cylinders (UHPC) with dimensions H/Ø=200/100 mm corresponding to the dimensions of driven piles in specialist foundation engineering. The cylinders were subjected to the repeated impact of a weight falling from a height of 600 mm until the ultra sonic pulse velocity, measured between the cylinder ends, decreased by 10% with respect to the initial value. The number of impacts necessary was defined as the impact failure number and was used to characterize impact resistance. Fibre type and content as well as concrete composition were varied.

Impact failure number and therefore impact resistance increased with the content of micro steel fibres in the concrete; from 4 for concrete without fibres to 41 and 98 for fibre contents of 1.5 and 3.0 vol.%, respectively.

In a series of investigations, either 1.25 or 0.5 vol.% straight steel fibres Ø = 0.4 mm together with either 1.25 or 0.5 vol.% crimped steel fibres Ø = 0.5 mm, respectively, were added to a mix with 0.5 vol.% micro steel fibres and compared with results for concretes reinforced with micro steel fibres alone. Volumetric replacement of micro steel fibres by the coarser fibres led to a reduction in impact resistance. In investigations on the effect of concrete additions in the mix it was noted that replacement of quartz flour by ground limestone resulted in a reduction of impact resistance; the impact failure number decreased from 25 to 18. A total of 17 impacts were required for the failure of a concrete in which the Portland cement content was strongly reduced by replacement with ground granulated blast-furnace slag and ground limestone. The results show that the impact resistance of ultra high strength concrete is mainly determined by the type and amount of steel fibres rather than binder composition.

On the whole, experimental tests indicate a promising application of UHPC for driven piles in specialist foundation engineering. This was shown by, among other things, the successful results of a practical driving test with a UHPC pile.

ACKNOWLEDGEMENTS

The authors would like to thank the German Federal Ministry of Education and Research for providing financial support in the WING programme (FKZ: 13N10457). Thanks are particularly due to Karsten Beckhaus and Hursit Ibuk of the specialist foundation engineering company BAUER Spezialtiefbau GmbH for their active cooperation and support. We are also grateful for the provision of the testing equipment by Christian Grosse, Ronald Richter and Erhard Westiner at Centre for Building Materials, Technische Universität München, Munich.
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