Properties and applications of DUCON® A micro-reinforced ultra-high-performance concrete

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ABSTRACT: The main advantage of DUCON (DUctile CONcrete), a patented 3-D micro-reinforced, self-compacting Ultra High Performance Concrete, is its ductility in combination with high compressive and flexural strength. This paper describes the properties and recent applications of DUCON. The material proved to have exceptional advantages as explosion resistant and bullet/fragment proof material. Explosion tests performed showed high energy absorption and ductility, i.e. no failure and no fragment projectiles. Special sniper projectiles which easily penetrate standard reinforced concrete can be stopped by DUCON panels. The main field of applications and projects realized so far are therefore the protection of critical infrastructure, such as military and public buildings, embassies, power plants, banks and data centers and ammunition storage tanks. Here, DUCON is used in new structures or for retro-fitting of existing structures in slabs and walls (fragmentation protection), for column protection, protective elements, etc. Moreover, other engineering and architectural projects realized such as industrial overlay, retro-fitting of columns for earthquake protection, slim façade panels and interior design elements show the great variety in applications of the material.

1 MATERIAL

1.1 Composition and material characteristics

DUCON stands for DUctile CONcrete and represents the combination of a high-performance or ultra-high-performance concrete and a micro-reinforcement from steel wire meshes (Fig. 1), developed by Hauser. The micro-reinforcement is uniformly distributed all over the cross section which results in a homogeneous composition of the composite material (Hauser 1999, Hauser & Wörner 1999). It consists of multiple layers of meshes with variable mesh width (between 6 mm and 35 mm) which are 3-dimensionally connected. Table 1 shows the most important material characteristics.

Table 1. Material characteristics.

<table>
<thead>
<tr>
<th>Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength</td>
<td>90–180 N/mm² (cube)</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>16–75 N/mm²</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>9–20 N/mm²</td>
</tr>
<tr>
<td>Shear strength</td>
<td>3–16 N/mm²</td>
</tr>
<tr>
<td>Modulus of elasticity</td>
<td>&gt;35,000 N/mm²</td>
</tr>
<tr>
<td>Thickness</td>
<td>≥10 mm–500 mm</td>
</tr>
<tr>
<td>Ductility factor</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

1.2 Production

Production is based on the placement of the prefabricated micro-reinforcement and the infiltration of the concrete slurry (Fig. 2). Between 1 Vol.-% and 10 Vol.-% of micro-reinforcement are embedded, typically, 6 Vol.-%.

Due to the fine mesh size of the micro-reinforcement, the crack width can be reduced to values of $w < 0.1$ mm which qualifies DUCON as...
impervious material. Thus, DUCON can be executed with a small concrete cover of a few millimeters compared to 20 to 50 mm of standard reinforced concrete.

1.3 Flexural strength and ductility

One major benefit of DUCON is that the material performance is programmable. Various set-ups and qualities of the micro-reinforcement (e.g. steel characteristics) allow the adaption of the material performance to the specific application. Figure 3 shows a stress-deflection diagram from flexural bending strength tests (Fig. 4) with three different possible adjustments A, B, C in comparison with standard concrete and typical fiber-reinforced concrete. Note that the curves for standard concrete (grey) and fiber-reinforced concrete (blue) are shifted horizontally for a better legibility.

Besides having high compressive and flexural strength, the properties can thus be adjusted to achieve an extremely ductile material. The ductility and its high strength are the key characteristics for high energy absorption of high speed dynamics and dynamics in combination with large deformations.

Compared to other ductile materials DUCON provides a high load bearing capacity at the same time (Fig. 4). The specimen as shown in Fig. 4 had a maximum deflection at a failure of 75 mm at 540 mm span. These characteristics are required for building protection for example against explosion and earthquake. Figure 5 shows a comparison of the flexural behavior of DUCON in comparison with a typical Engineered Cementitious Composite (ECC, Wang & Li 2006) and a standard concrete.

Whereas “ECC has approximately half the flexural strength of Ductal (another ultra-high-performance concrete) but 20 times its tensile ductility” (Smock, 2007), DUCON exhibits even more than twice the tensile ductility of ECC and more than 4 times its flexural strength.

2 Dynamic Properties

2.1 Blast resistance

Figures 6 and 7 demonstrate the resistance of DUCON against close range and contact charges compared to reinforced concrete (RFC) at the same thickness of...
Figure 6. Reinforced concrete fails under contact charge. Full penetration + fragment projectiles.

Figure 7. DUCON remains stable, no penetration nor fragment projectiles, 85% of the cross section stays intact.

Figure 8. Finite-element simulation of DUCON under contact charge load.

150 mm (RTL TV broadcasting, 2004). The reinforced concrete failed, the blast wave penetrated the panel and in addition created fragment projectiles. DUCON resisted the blast test and no penetration or fragments could be observed.

Several blast tests of the Fraunhofer Institute and for the US Military (Schuler & Mayrhofer 2004, Schuler & Mayrhofer 2007, Marchand 2007) proved that the blast resistance of DUCON is at least twice as good as of ordinary reinforced concrete, which means it can be executed at half the thickness and in addition it does not spall.

The 3-dimensional micro-reinforcement keeps the structural integrity of the concrete and avoids spalling and fragment projectiles.

The material properties of DUCON have been recently implemented into a finite element code for high-speed dynamics (Fig. 8, Gebbeken & Greulich, 2006).

2.2 Ballistic resistance

According to the blast resistance DUCON proved a comparable performance in ballistic resistance. It reaches the resistance of reinforced concrete with less than 50% of the thickness. Moreover, the special 3-dimensional micro-reinforcement allows a structural integrity of the concrete and avoids spalling.

Figure 9 shows that a 100 mm thick DUCON panel absorbed armor piercing bullet (Wolfram-Carbit penetrator at a speed of 840 m/s) while RFC needed to be 24 cm. Bullet tests resulted in a PM7 (highest requirement level of European code) for a thickness of only 80 mm.

Further Military test series (Marchand 2007) proved that a 10 cm DUCON-panel also resists high velocity fragments of propeller drilled weapons, like Mortars in combination with explosion.

3 RECENT APPLICATIONS

3.1 Fragmentation protection for blast loading

Figure 10 shows an application of a DUCON layer (thickness 15 mm) acting as an integrated “safety-net” on the bottom of a reinforced concrete slab (thickness 300 mm). The tests performed proved the effectiveness of DUCON to remain the structural integrity of the slab under blast loading. This application has been used several times to protect the server room of high security data centers in Europe. It was also used for the concrete walls.

3.2 Blast protection wall and blast protection facade

In these applications, DUCON has been used as protective walls and secondary facades in front of endangered buildings. Walls have a typical thickness of 100 mm to 250 mm, façade elements a typical
Figure 10. DUCON panel, thickness 15 mm, acts as an integrated “safety-net” on the bottom of a reinforced concrete slab.

Figure 11. DUCON wall, thickness 250 mm, acts as protective element in front of an embassy.

Figure 12. Retro-fitting of existing columns for earthquake protection.

Figure 13. DUCON tubes used as integrated formwork for reinforced concrete columns.

Figure 14. DUCON overlay, 25 mm, applied on an existing cracked concrete slab of a chemical plant.

3.3 Blast protection columns

Here, two types of production have been applied: a retro-fitting of existing columns (Fig. 12) or tube columns made of DUCON used as integrated formwork (Fig. 13). They have been applied for earthquake protection (Zekaria 2001) and for blast protection (Schuler & Mayrhofer 2007).

3.4 Impervious and abrasive resistant overlays

Based on the high performance material characteristics of DUCON, impermeability, durability, freeze-thaw resistance and corrosion resistance in combination with crack control have been tested for the International Code Council (ICC) approval which was obtained for the applications on the US market.

These characteristics are well suited for applications of thin impervious overlay on top of existing or damaged flooring or concrete structures.

Figure 14 shows an application at a chemical plant where 7.500 m² of damaged and cracked concrete

thickness of 40 mm to 150 mm. The DUCON panels are prefabricated elements and can be easily transported and installed. Figure 11 shows an embassy in Europe protected by a DUCON wall.
Figure 15. Entrance portal of DUCON, height 4.50 m, span 4.50 m, thickness 80 mm to 100 mm.

A slab could be quickly repaired by a 25 mm DUCON overlay and a time- and cost consuming demolition and reconstruction of the concrete could be avoided.

3.5 Architectural applications

Beside thin plates for tables, façade panels or counter tops, recently also structural elements have been produced. Figure 15 shows an application as an entrance portal, height 4.50 m, span 4.50 m with a thickness of only 80 mm to 100 mm. The portal was pre-fabricated and installed on site.

Thin members of concrete for free-form applications are another future possibility as the micro-reinforcement can be adapted to any shape by hand.

4 CONCLUSIONS

DUCON, a very ductile composite material of concrete and steel, shows excellent material properties and a large spectrum of applications. Its high energy absorption allows applications for blast and ballistic protection without fragmentation at approximately half the thickness of ordinary reinforced concrete.

Future applications and research should also consider the stability behavior of the material, e.g. for shells and thin membranes and should develop new connections.

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REFERENCES
