HIGH STRENGTH FIBRE REINFORCED CONCRETE (HSFRC) UNDER HIGH DYNAMIC IMPACT LOADING

Andrea Kustermann, Manfred Keuser
University of the Federal Armed Forces, Munich, Germany,

Abstract

High Strength Concrete (HSC) is an improved material which is used for high-rise buildings, bridges and offshore constructions. The addition of fibers in the HSC gives a significant increase of ductility, reduces shrinkage effects and ameliorates the resistance against mechanical attacks. The material properties indicate, that High Strength Fibre Reinforced Concrete HSFRC must be a well-suited material for protection against impact loading with high dynamic effects.

The German Ministry of Defense has supported a research project of the University of the Armed Forces in Munich. The aim of the project was the development of materials and structures, which are able to resist high dynamic impact loadings. Several barriers made of different admixtures were tested under gun fire with a maximum velocity of 890 m/s. Concrete mixtures with short steel fibers showed an optimal compromise between workability, improved ductility and protection against impact. The additional use of polypropylene fibers lead to a higher ductility of the concrete slabs. Due to the increased tensile strength, the scabbing damages at the rear side, caused by the reflection of the tensile wave, are significantly reduced.

1. Introduction

Since some years the importance and the volume of out-of-area activities of the German armed forces have increased significantly. The protection of soldiers and material requires a completely new equipment, especially with regard to terrorist attacks. In order to establish a basis for the design of a protection system which includes HSFRC slabs, a research project at the University of Federal Armed Forces Munich has been funded by the German Armed Forces. [1, 2]. The aim of this research project was the development
of concrete mixtures with a high compressive strength, a high ductility and a high resistance against impact loading with high dynamic effects. A study of the material behavior of HSFRC under impact loading with extremely high strain rates is described in this paper.

2. Load carrying behavior of concrete slabs under impact loading

The load carrying behavior of concrete slabs under impact loading is a large field of experimental and theoretical investigations. The main problem is the interaction between high strain rates up to 10^-8/s and the nonlinear behavior of concrete [3]. The extremely high strain rates are accompanied by very high pressures thus experimental data concerning the increase of the material strength and the deterioration caused by compression and tension only can be obtained by sophisticated methods like Hopkinson-bar tests or planar-plate-impact tests [4]. As a consequence, the use of numerical models is restricted to special applications. They are mostly based on the hydrocode method [5, 6].

When the projectile hits the material, a compressive wave is initiated by the impact (Fig. 1). This compressive wave runs through the material to a free edge. The wave is reflected there and transmutes into a tensile wave which propagates in the opposite direction [7]. Eibl [7] et al. observed local failure mechanisms especially in the first phase of impact which were caused by the very concentrated shock wave. The main failure modes are spalling at the front side and scabbing on the rear side of the loaded slab. (Fig. 2)

![Diagram of load carrying behavior after an impact loading on a target]

Fig. 1: Load carrying behavior after an impact loading on a target.
Zukas [9] defines three ranges of impact velocity with different failure modes:

- At velocities below 250 m/s local deformation and penetration of the test specimen are related to its global deformations. The load carrying behavior of the complete structural part is activated.
- In the medium velocities range between 500 and 2000 m/s impact principally leads to local effects. The material reaction in the impact zone can be described by a wave theory using elastic or nonlinear material models. The diameter of the impact zone is about three times the diameter of the projectile.
- Higher velocities of the projectile cause explosive vaporization of the materials. The investigation of the impact resistance in the velocity range of about 900 m/s will be described in this paper. Dancygier and Yankelevsky [10, 11] conducted many investigations determining the impact depth of projectiles in normal strength and high strength concrete with and without reinforcement. They also evaluated and developed several mathematical models describing the penetration depth of projectiles in concrete.

The advantages of high strength concrete compared to normal strength concrete under hard projectile loading are also confirmed by tests of Dancygier [12]. Targets made of high strength concrete were not perforated in his tests, while similarly reinforced specimens of normal strength concrete were perforated. High strength concrete requires a higher projectile velocity to be perforated due to its higher perforation resistance compared to similar normal strength concrete slabs. Markeset [13] investigated the relationship between compressive strength and penetration depth, as shown in Fig. 3. The penetration resistance enhances by increasing the compressive strength from 30 to 150 N/mm². But a further increase in compressive strength does not seem to give a significant improvement.
Dancygier and Yankelevsky [14] ascertained in their investigations that the use of fiberglass reinforcement enhanced the ductility and toughness of the rear side and avoided scabbing at the rear side of the slab. Former tests at our Institute showed that the addition of fibers does improve the penetration resistance, above all at the rear side of the specimen where the tensile wave takes effect. [1, 2, 15] Specifically, the use of steel fibers ameliorates the ductility, which is essential at the rear side of the concrete slab.

3. Testing Equipment

The penetration tests have been carried out with several slabs, using the same test equipment. The slabs were made of plain concrete with different thicknesses. They have been fired with a high-speed gun. The projectiles (7,62x54R) had an initial velocity of 890 m/sec. The test-specimen and the test setup are shown in Fig. 4 and Fig. 5.

The distance between the gun and the tested concrete slabs has been varied between 25 m and 100 m. The results show that the damage has its maximum for a 50 m-distance, although the velocity reduces from 890 m/sec in the gun to 850 m/sec when the projectile hits the HSC slab in a distance of 100 m. The reason therefore is the stabilization of the projectile during its flight. By its rotation, the projectile reaches a stable position in a distance between 50 and 100 m and the effects of its distraction by hard aggregates is minimized. Shorter and larger distances can influence the results significantly. The angle of 90 degrees between the front of the concrete slab and the projectile’s direction is the worst case with the highest damage potential.
4. Investigated Parameters

In this project a large scale of aggregate materials and particle size distribution have been tested as well as slabs with different thicknesses, different ages and different distances between the gun and the tested slab. Main theme of this paper is the variation of the used fibres. In the tests the volumes of the craters caused by spalling and scabbing have been measured as well as the residual energy of the projectile in case of total penetration through the slab.

5. Influence of fibers on the impact resistance

Experiments with steel fibers, glass fibers and polypropylene fibers of different dimensions were performed to find an effective type of fiber for a high impact
resistance. Steel fibers show a significant improvement of the hardened concrete properties. Their Young’s modulus is two to three times higher than the Young’s modulus of glass fibers. The addition of steel fibers with a length of more than 6 mm causes the buildup of clumps and leads to both a reduced workability of the fresh concrete and unsuited properties of the hardened concrete. Additionally the longer steel fibers cause more effort in production because they have to be added by a sieve into the mixture.

Glass fibers have a high Young’s modulus and a high tensile strength. The development of alkali resistant glass fibers allows an application of this fibers in cement bound structures. Glass fibers also admit an acceptable workability of the fresh concrete.

Mixtures containing polypropylene fibers have a better workability in relation to other fibers even if long fibers are used. The buildup of clumps is neglectible. Additionally a so-called “fiber cocktail” was tested. The fiber cocktail consists of steel and polypropylene fibers. The steel fibers cause an improvement of the hardened concrete properties, they increase the ductility and decrease the Young’s modulus. The addition of polypropylene fibers ought to reduce the crater volume caused by spalling and scabbing. The concrete mixtures with the fiber cocktail show an ameliorated post peak behavior in the stress-strain curve.

For the experimental tests the following types of fibers were used:
- steel fibers, length 6 mm, round profile, diameter 0.16 mm
- steel fibers, length 13 mm, round profile, diameter 0.16 mm
- steel fibers, length 20 mm, rectangle shape, 1 mm x 0.026 mm
- glass fibers, length 12 mm, diameter 0.014 mm
- polypropylene fibers, length 32 mm, diameter 0.10 mm

A reference HSC mixture with a water-/binder- ratio of 0.34 was used to compare the influence of the different types of fibers. The mixtures containing the fiber cocktail had a water-/binder- ratio of 0.32. All mixtures contained silica fume and crushed quartzite with a maximum particle size of 16 mm as aggregate. The amount of fibers added was 1 vol.-% for the single fiber types and 1.7 vol.-% for the fiber cocktail. The fiber mixtures showed a higher water demand and a stiffer consistency of the fresh concrete than the reference mixture without fibers because of the large surface of the fibers. For the fiber cocktail the amount of paste was increased to ensure a better workability of the fresh concrete.

The values of compressive strength are nearly the same for all specimen between 110 and 125 N/mm². The Young’s modulus of the mixtures containing glass fibers is always lower than of the mixtures containing steel fibers. Fig. 6 also shows the influence of the polypropylene fibers. The Young’s modulus of the fiber cocktail mixture which contains additional polypropylene fibers is significantly lower than that of the mixture with the 6 mm steel fibers.
The results of the impact tests on fiber reinforced slabs compared to a slab without fibers are shown in Fig. 7. The fiber-reinforced slabs have a better performance concerning spalling and scabbing. The craters in these slabs are significantly smaller than those in slabs using mixtures without fibers. The glass fibers behave very brittle in response to a shearing load and the slabs made from a mixture containing glass fibers showed a high damage on the rear side. The mixtures with the 6 mm steel fibers and the fiber cocktail mixture show the best results with a minimum crater volume. The 13 mm steel fibers and the 12 mm glass fibers show a higher spalling than the shorter steel fibers and the fiber cocktail. The rear side crater volumes of the slabs with glass fibers are very high. The fiber cocktail showed the expected optimal results. The crater volumes are lower than the crater volumes of the slabs containing other fiber mixtures due to the added polypropylene fibers which allow an adherence of the occurring cracks and craters. The number of witness shields indicate the residual energy after penetrating the slab. The slab with the fibre cocktail was not penetrated.

The comparison between compressive strength and crater volume shows in Fig. 8, that the compressive strength is not the only important concrete property. The increase of the uniaxial compressive strength to values higher than 100 N/mm² does not give an increase of resistance against impact. Due to the fiber addition ductility and post peak behavior influence the resistance against high dynamic impact loading. In Fig. 9 the typical failure of HSC/HSFRC slabs loaded by impact is shown. The slabs are sawn directly through the crater and the projectile in the concrete.
Fig. 7: Comparison of the crater volumes at the front and rear side of concrete slabs, thickness 10 cm, distance 50m/100m

Fig. 8: Comparison between Crater volume and Compressive strength of different HSC mixtures with and without fibers
Fig. 9: Cross section of a slab without fibers (left) and a slab containing steel fibers 6 mm (right) after impact loading

6. Conclusions

HSFRC is a well suited material to protect human beings against impact loading and blasting. Concrete is able to be made for different protection applications, like accommodations, tunnels, ammunition camps and protection walls. The advantage of concrete and especially the HSC and HSFRC is the good penetration resistance also as well as the possibility to produce the material nearly anywhere. Special material should be obtained, but the main part of the mixture, the aggregate can be obtained in situ. A slab thickness of 8 to 10 cm is – using an appropriate concrete mixture – a safe solution to protect human beings against gun fire.

Experimental studies with different thicknesses and HSC mixtures show clearly that the resistance against impact loading does not only depend on the uniaxial compressive strength. As the failure mechanisms strongly depend on local and global stiffness distributions the increase of ductility is a promising way to develop a safe protective system using HSFRC slabs. A special fiber mixture shows best results for protection elements against impact.

References


