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Study of fractured surfaces of concrete caused by projectile impact

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ABSTRACT

In recent years several studies presented different parameters and criteria to describe the damage of concrete specimens caused by projectile impact. The parameter used most to characterize damage is the volume of the craters on the front and rear side of the concrete specimen. In this study the damage of concrete specimens is described as a fractured area. In order to describe the whole fractured area it is necessary to consider the crater surfaces and the fractured surface area of the fragments generated by impact. The crater surfaces were analysed using a 3-dimensional laser-scanner system. The fragments were measured with a camera particle analyser. Their surfaces were determined taking into account the following parameters: Feret diameter, length, volume distribution and sphericity. A triaxial ellipsoid model was developed by means of these parameters. The whole fractured surface area is given by the sum of the specimen surface after perforating and the fragments surface minus the specimen surface before perforation. The fragment surface is decisive for the fractured surface and depends on the number of fragments of each size class. This study confirms previously gained results using new parameters: A larger maximum aggregate diameter enhances the impact resistance of concrete against projectiles.

1. Introduction

Protective structures for military and civil applications are generally made of concrete. Within the design of protective structures the compressive strength is the concrete property used most. However, Dancygier et al. [1] showed that this single parameter is insufficient to describe the local effects of a projectile impact. In particular, parameters describing the composition like steel fibres, the hardness and type of the aggregate, the use of silica fume amongst others have to be considered. Kustermann et al. [2] identified the maximum aggregate diameter as a decisive composition parameter for impact resistance of concrete.

A review of empirical, analytical and numerical formulae to describe impact effects on concrete is given in Li et al. [3]. In this context, they describe four parameters measured most frequently to characterize the penetration behaviour of projectiles into concrete targets: penetration depth (without perforating a massive concrete target), scabbing limit (minimum target thickness to prevent scabbing), perforation limit (minimum target thickness to prevent perforation) and ballistic limit (minimum initial impact velocity to perforate the target). Additionally, the sizes of the craters on the front and rear side are often taken into account. By means of these parameters different types of damage can be described, see Zukas [4]. Typical damages of concrete targets are spalling and scabbing accompanied by craters on the front and rear side. Further damages may include cracks, perforation, local plugging and/or global failure as shown in Fig. 1.

In this study the damage of concrete targets is described as total fracture area. In order to describe the whole fractured area the crater surfaces and the fractured surface area of the fragments generated by impact are included. Three concrete compositions with different maximum aggregate diameters (4 mm, 8 mm and 16 mm) were investigated. The ratio between the volume of the cement-matrix and the volume of the aggregate was kept constant.

2. Experimental overview

2.1. Concrete compositions and preparation of specimens

In order to obtain a normal strength concrete, German CEM I Portland cement was used with a minimum strength of 42.5 N/mm^2 at 28 days. The ratio between water and cement was 0.60. The aggregate was limestone from a local quarry with a maximum diameter of 4 mm, 8 mm or 16 mm, respectively. The ratio between the volumes of the cement-matrix and the aggregate was constant. Details of the mix designs are given in Table 1.

Experiments on the impact resistance were conducted on ten specimens of each concrete composition. The specimens had a quadratic loading area with an edge length of 300 mm and

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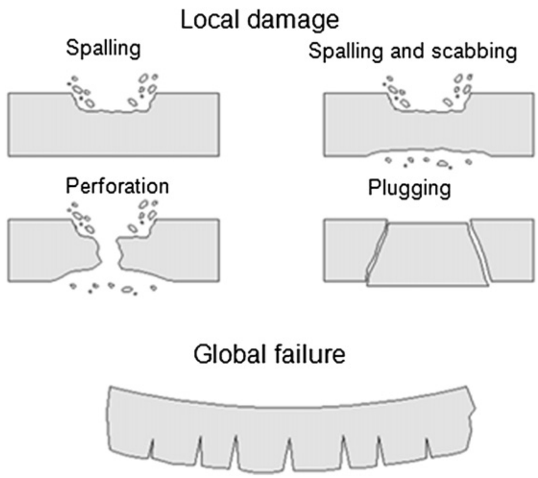

Fig. 1. Global failure and local damages according to Ockert [5].

a thickness of 50 mm. The thickness was kept relatively small to guarantee a perforation of the specimens. The specimens were demoulded after one day and subsequently stored in lime-saturated water until they were ready for testing at an age of 28 days.

2.2. Concrete properties

Compressive strength f_c and Young's modulus E were determined in each case from three cylindrical specimens ($d/h = 150/300$ mm). The bending tensile strength f_{ft} was measured using three unnotched beams each ($l/w/h = 100/100/500$ mm) in 3-point bending tests. All mechanical properties were determined at an age of 28 days according to DIN EN 12390 [6]. Additionally, the static fracture energy G_F according to RILEM [7] was measured for ten beams ($l/w/h = 840/100/100$ mm). The mean values obtained and their coefficients of variation are presented in Table 2. The strength f increased slightly for concrete mixtures with decreasing maximum aggregate diameters while density ρ, Young's modulus E and fracture energy G_F decreased.

2.3. Experimental investigation

2.3.1. Impact investigation

The impact investigation was carried out with a measuring weapon system of Mauser. The specimens were installed in a steel frame inside a backstop and aligned such that the projectile would hit the specimen centre. The experimental set-up is presented in Werner et al. [8]. The munitions used were jacketed projectiles with a hard core of tungsten carbide and a weight of 9.5 g ($d/l = 7.62/51$ mm). Such projectiles are special munitions of the German army.

The striking velocity of the projectile was set to 870 m/s so that the striking kinetic energy was approximately 3600 J. The accurate striking velocity was measured by light barriers. The velocity of the projectile after perforating the specimen was measured with a double exposed picture of a digital camera. As a result of the 2-dimensional picture a minor defect of the velocity calculation occurred in cases where the projectile was diverted outside the field of view. These cases could not be measured with the method applied. The kinetic energy after perforating was calculated by means of the velocity measured. The difference of the kinetic energy of the projectile before and after perforating is mostly absorbed by the specimen. In some tests, the projectile was spun by coarse aggregates so that the kinetic energy after perforation decreased further due to the spin. This additional energy absorption of the specimen was not analysed.

After each test, the specimen was removed from the backstop and the ejected concrete fragments were collected with a vacuum cleaner. By weighing the specimen (and the ejected fragments) before and after each test, the loss in mass could be calculated.

Table 1
Mix design.

Specimen designation	W/c [-]	Water [kg/m^3]	Cement [kg/m^3]	Sand 0/4 [kg/m^3]	Gravel 4/8 [kg/m^3]	Gravel 8/16 [kg/m^3]
NSC 16	0.6	185	310	847	364	680
NSC 8	0.6	185	310	1268	619	0
NSC 4	0.6	185	310	1879	0	0

Table 2
Mechanical properties (in parentheses: coefficient of variation).

Specimen designation	ρ [kg/dm^3]	f_c [MPa]	E [GPa]	f_{ft} [MPa]	G_F [N/m]
NSC 16	2.489 (0.007)	46.7 (0.025)	32.6 (0.033)	6.1 (0.033)	97.4 (0.143)
NSC 8	2.404 (0.005)	48.8 (0.019)	29.6 (0.010)	7.3 (0.020)	88.0 (0.126)
NSC 4	2.277 (0.003)	49.4 (0.019)	27.2 (0.014)	7.9 (0.061)	80.9 (0.101)

2.3.2. Crater surface investigation

The crater surface areas on the front and rear side of the specimen were measured with the 3-dimensional laser scanner DAVID 3D. It is a system which consists of the software DAVID and the following hardware components: a line laser, a digital camera and a 90°-edge with a specific pattern (reference geometry). The specimens were placed central in front of the 90°-edge like it is shown in Fig. 2.

The scanning system is based on laser triangulation. Therefore, the laser plane of the line laser intersects with the calibration points of the background reference geometry. The camera records the laser plane and the software calculates the coordinates of single points of the surface area in real-time. As a result, the points scanned form a 3-dimensional point cloud defining the surface area which then in turn can be calculated. The DAVID 3D laser-scanner is suitable mainly to scan relatively small objects as a consequence of the measurement setup. The detailed principle is described in Winkelbach et al. [9].

2.3.3. Fragment surface investigation

Two methods were used to calculate the fragments surface area: a computer particle analyzer (CPA) for fragments with at least two dimensions <25 mm and a scanning method for larger fragments. The fragments were classified by sieving through a 25 mm sieve.

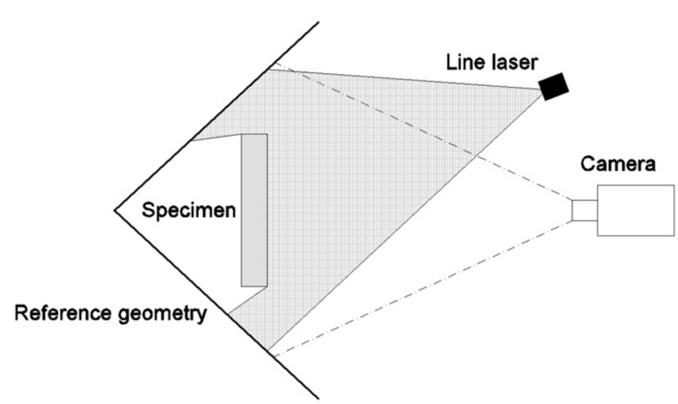

Fig. 2. Measurement setup for the contact-free scanning of 3-dimensional objects with DAVID 3D (top view).