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Rebound and orientation of fibers in wet sprayed concrete applications

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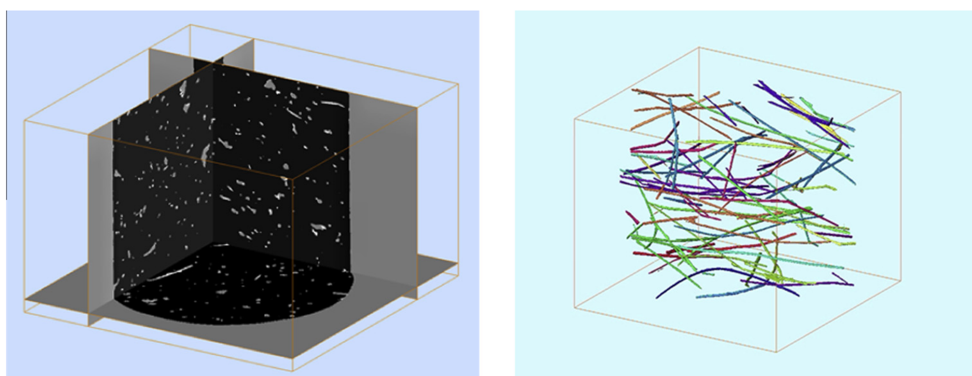
HIGHLIGHTS

- Detailed analysis of the impact behavior of fibers in sprayed concrete.
- Usage of artificial walls with defined surface to determine the rebound.
- Reconstruction of 3D fiber orientation applying morphological filtering methods.
- Evidence for a preferred fiber orientation perpendicular to the spray direction.

GRAPHICAL ABSTRACT

X-ray computer tomography reveals fiber orientation perpendicular to the spray direction for both steel and macro-synthetic polymer fibers.



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ABSTRACT

Spraying of concrete is a well-established and economical alternative to conventional casting techniques. It is widely applied in repair/reinforcement of building elements, rock consolidation and for the construction of temporary or permanent tunnel linings. Sprayed concrete (shotcrete) may be reinforced with fibers, steel rods or steel meshes to increase its mechanical performance under bending. In wet spraying, the concrete is premixed with water and then sprayed by means of compressed air. The fibers are added to the fresh concrete and then sprayed together with it. Because of their high elastic modulus and tensile strength often steel fibers are used for such applications. Recently, macro-synthetic plastic fibers have been proofed to be a suitable non-corroding alternative.

The mechanical performance of fiber reinforced shotcrete is mainly influenced by the amount, the distribution and the orientation of the fibers, which are parameters that are influenced by the special application technique. Because of the relatively high impact velocity, the concrete and the fibers do not adhere completely onto the treated surface and generally a large quantity of rebound is observed.

The rebound behavior of macro-synthetic polymer fibers and of steel fibers was studied in field tests as well as in laboratory experiments. Concrete was sprayed on well-defined artificial stone reliefs and the fiber as well as the material rebound was collected and analyzed. On the example of macro-synthetic fibers, the influence of different fiber parameters on the rebound behavior was studied. Single fiber shoot-

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ing experiments and direct observations by means of a high speed camera revealed their impact behavior and hence the causes for fiber rebound.

The fiber orientation in sprayed concrete was analyzed by means of X-ray computer tomography. Special morphological filtering allowed the analysis of the properties of plastic fibers despite their low density. A preferential orientation of these fibers along the sprayed surface was observed.

1. Introduction

Fiber reinforced shotcrete was first experimented in the early 1970s with the first major field application in 1973. The addition of steel fibers to normal shotcrete led to a significant improvement in the toughness or energy absorption capacity. Therefore, it resulted in an economically and technically equal or superior alternative to conventional sprayed concrete using wire mesh [1–3]. Since then, this material was widely applied in mining operations and for forming linings in various railway, road and water tunnels. Steel fibers are selected because of their relatively high elastic modulus and tensile strength. More recently, macro-synthetic plastic fibers have been developed and are promoted as a non-corroding alternative to steel fibers.

In the wet spraying technique, the fibers are added to the premixed concrete and then the fresh concrete is pumped to the nozzle, where it is accelerated by compressed air and sprayed to the application surface. At the nozzle, liquid additives like setting accelerators are added, so that the concrete already reaches certain stiffness upon arrival on the surface area. Besides the high impact velocity, this is a further cause for incomplete adhesion of shotcrete on the surface, so that an important rebound of concrete and of fibers results.

Armelin and Banthia [4] studied the mechanics of aggregate rebound in shotcrete applying a high speed camera. He concluded that the adhesion between the particle and the substrate must be regarded as the main mechanism involved. Lower aggregate density and the addition of fine particles were suggested to reduce aggregate rebound [5,6]. Austin et al. [7] found no significant influence of fiber addition nor fiber geometry or fiber mass on the material rebound and reported that variations in spray conditions had a higher effect.

Coarse aggregates and especially fibers tend to rebound more than for the rest of the shotcrete components and hence the material in place is deficient in these phases. While the loss of aggregates or other mineral concrete components mostly affects the work efficiency, the loss of the reinforcing fibers has a significant impact on the mechanical properties of fiber shotcrete. The fiber rebound mostly has been studied on steel fibers. The rebound of steel fiber was found to increase with higher aggregate to cement ratio, while the addition of fine powders like metakaolin, fly ash or microsilica lead to less fiber rebound [6]. Steel fiber rebound was found not to be related to the fiber geometry in a wet-process [8].

Macro-synthetic polymer fibers in wet-mix shotcrete application have grown significantly worldwide since their introduction in the late 1990s. While the stiffer steel fibers are used at relatively short length (30–35 mm) to reduce lime blockage, the more flexible macro-synthetic polymer fibers can typically be used with larger length (40–60 mm) without significantly reducing the pumpability and sprayability of the mixture. Macro-synthetic polypropylene fibers were found to lead to a reduction of fiber loss due to rebound and an increased shotcrete layer built-up thickness [9].

A further development and modern fiber technologies (co-extrusion) allows for the production of bi-component fibers, which possess a sheath and a core, which may consist of different polyolefin polymers [10] so that the sheath may be optimized regarding adhesion and bonding, while the core delivers adequate mechanical properties.

Besides rebound, a further important aspect is the orientation of the fibers on the treated surface area as the fiber orientation significantly influences the mechanical properties of a composite. Because of the special application technique preferential alignment may be expected. However, only very little is known about the fiber orientation in fiber reinforced shotcrete. A preferred orientation of steel fibers perpendicular to the spray direction is found analyzing cut sections [11,12]. In this work, the rebound and the rebound mechanism of fibers in shotcrete was studied in fiber shooting experiments in the laboratory on the one hand and under field conditions on the other hand. The orientation of the steel and polymer fibers was analyzed based on X-ray computer tomography.

2. Materials and methods

2.1. Single fiber shooting set-up

To study the impact of a sprayed fiber on a wall, a novel single fiber shooting set-up (Fig. 1) was built. It consisted of an air gun, which could be aligned to a desired target. One single fiber was loaded into a 0.8 mm (inner diameter) tube and then shot by instant release of compressed air with a well-defined pressure (adjustable 0–8 bar) into the tube by pushing a button. While in the case of the plastic fibers the gun could be charged with the original fibers at the backside of the 30 cm long tube, the hooked steel fibers were loaded at the exit side of the tube. At one end the hook was removed to facilitate shooting, so that only the impacting fiber end remained hooked.

The fiber impact on the wall, which was situated at a distance of 50 cm from the shooting gun, was monitored by means of a high speed camera (Kodak Ektapro motion analyzer) at a frequency of 4500 images per second (256 × 256 pixel, 256 grey levels per pixel). The fibers were shot on freshly applied mortar to simulate realistic impact conditions.

2.2. Field spray tests

In field spray tests, the fiber and the material rebound of sprayed concrete was measured. To obtain similar surface to spray on, large artificial concrete walls of $3.50 \times 1.39\ m^2$ with a well-defined surface structure (artificial stone profile Cheyenne_2_121G, Reckli AG, Switzerland, Fig. 2) were fabricated.

The sprayed concrete (CEM I 42.5 N: 450 kg/m^3, sand 0.1 mm: 116 kg/m^3, sand 1.4 mm: 958 kg/m^3, gravel 4.8 mm: 578 kg/m^3, superplasticizer viscocrete SC-305 (polycarboxylate-ether-based, Sika Switzerland): 2.7 kg/m^3 (0.6% of cement), delvocrete stabilizer: 0.45 kg/m^3 (0.1% of cement), w/c = 0.45) was premixed for 2 min and then the fibers were added and further mixed for another 2 min.

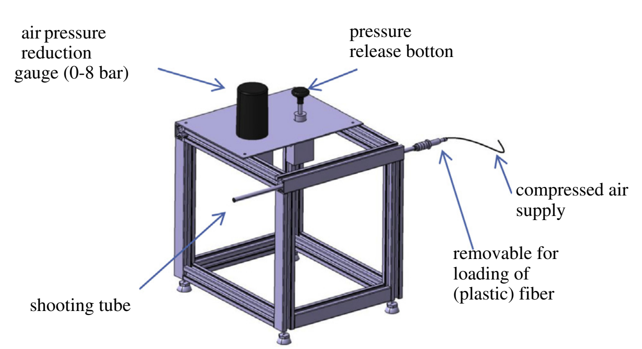

Fig. 1. Single fiber shooting set-up.