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Performance of shotcrete containing amorphous fibers for tunnel applications

Jun-Mo Yang [a], Jin-Kook Kim [a], Doo-Yeol Yoo [b,]*

[a] Steel Structure Research Group, POSCO, 100, Songdogwahak-ro, Yeonsu-gu, Incheon 21985, Republic of Korea
[b] Department of Architectural Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea

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ABSTRACT

The role played by a number of fiber properties (like fiber length, content, type, hybridization, tensile strength and energy-absorption capability or toughness) is investigated in this paper with reference to shotcrete mixes containing amorphous fibers with random atomic arrangement (well known for their excellent corrosion resistance) and conventional hooked steel fibers. Several prismatic beams and plates were cast by varying the above-mentioned properties. Compared to steel fiber-reinforced concrete (SFRC), amorphous metallic fiber-reinforced concrete (AFRC) exhibits a higher flexural strength, but a lower residual strength in tension after first cracking, a lower energy-absorption capability, and a higher "rebound" ratio during the spraying process. The rebound is favored by the fiber ball in the case of amorphous fibers, while a relatively small number of steel fibers gives shotcrete a more cohesive behavior during the spraying process. Amorphous fibers are, therefore, more suitable for quick repairs (for instance, in sewerage pipes), whenever quick hardening and good short-term mechanical properties in tension are sought for, together with corrosion resistance.

1. Introduction

Many tunnels have been bored using the NATM (New Austrian Tunnelling Method) concept. Although the stability of tunnel structures is guaranteed within the NATM concept by the rock itself, typical cases involve tunnel supports such as rock bolts, shotcrete, and so on. As it is well known, shotcrete is cast by means of a process in which compressed air forces mortar or concrete through a hose and nozzle onto a surface. Shotcrete can play the role of a structural component within a very short time, and can be used to freely construct not only extremely thin elements but also very thick elements without any formwork. Therefore, shotcrete is being adopted in a wide range of construction projects including the repair and rehabilitation of concrete structures, the building of tunnel linings, and the stabilization of rock and soil slopes.

In the earlier days of shotcrete application, a wire mesh was placed prior to applying shotcrete to prevent cracking of the shotcrete layer. The wire mesh was difficult to install and resulted in a 'shadowing' effect, leading to the formation of large voids in regions where shotcrete may hardly penetrate the wire mesh itself. In order to overcome the problems associated with wire-mesh installation, structural fibers are incorporated and fiber reinforced shotcrete (FRS) is used in almost every tunneling project around the world. It is well known that in cementitious composites – and namely in shotcrete – fibers can effectively improve crack resistance, residual strength (after cracking), energy-absorption capability, and impact/fatigue/high-temperature resistance, as well as durability (Balaguru and Shah, 1992; ACI, 2005; Bamonte et al., 2016).

Numerous fiber types are available for commercial and experimental use. The basic fiber categories include steel, glass, synthetic, and natural fiber materials (ACI, 2001). Each fiber has its own unique merits and faults for each field application, and users generally have multiple options. Lately, a new type of fiber material has been developed, specifically amorphous metallic fibers (Fig. 1), which fall under the steel fiber category but have totally different mechanical properties compared with conventional steel fibers. Amorphous fibers have attracted attention from civil and architectural engineers due to several advantages, including a higher tensile strength, corrosion resistance, and a larger number of fibers per unit volume compared to ordinary steel fibers; thus, many studies on amorphous metallic fiber reinforced concrete (AFRC) are being performed (Choi et al., 2014; Dinh et al., 2016; Hameed et al., 2009; Won et al., 2012; Yoo et al., 2016b). High-performance amorphous fibers improve crack control (thanks to their high tensile strength) and reduce corrosion effects (thanks

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* Corresponding author.
E-mail address: dyyoo@hanyang.ac.kr (D.-Y. Yoo).

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Nomenclature

P	applied load	f^D_{600}	residual flexural strength at deflection of $L/600$
L	clear span length	f^D_{150}	residual flexural strength at deflection of $L/150$
b	beam width	T^D_{150}	toughness at deflection of 2 mm ($L/150$)
h	beam height	L_f	fiber length
T	toughness at the deflection point of δ ($L/600$ or $L/150$)	W_f	fiber weight
f_{MOR}	flexural strength	f_{ts}	fiber tensile strength

to their corrosion resistance), to the advantage of shotcrete durability. Furthermore, amorphous fibers are flexible and pliable between the fingers; therefore, amorphous metallic fiber reinforced shotcrete (AFRS) can be handled with conventional spraying devices.

This study investigates the applicability of AFRS in tunnel applications. To this end, the effects of variables such as the length, tensile strength, and quantity of amorphous fibers were examined because of their role in guaranteeing the performance of AFRCs. Additionally, the strength and ductility class of AFRC were investigated according to the European Specification for Sprayed Concrete (EFNARC, 1996). Finally, a field application test of AFRS was performed in the building site of a real tunnel.

2. Experimental program

2.1. Materials and mixture proportions

In this study, fiber-reinforced concrete (FRC) without an accelerator and FRS with an accelerator were mixed in the laboratory and in the field, respectively. The mixing proportions used in this study are provided in Table 1. In the case of the laboratory FRC mix, a water-to-cement ratio (W/C) of 0.426 was adopted. Type 1 Portland cement was employed. The mass ratio of sand and aggregates (sand + gravel) was 0.60. Coarse aggregates, with a specific mass of 2.69 kg/m^3 and a maximum size of 10 mm, were used. Fine aggregates were washed and had a specific mass of 2.59 kg/m^3. The target slump value was 120 ± 20 mm with an air content of 4 ± 1%. Polycarbonate superplasticizer was added to achieve the target slump value for each mix. In the FRS mix, the materials and mixture proportions used within the real tunnel construction site were employed, and they were similar to those used in the laboratory. The water-to-cement ratio (W/C) was 0.44 and the target slump value was 150 ± 20 mm. A high-strength cement-based mineral accelerator was employed, providing excellent early age strength development and a lower rebound of shotcrete (Won et al., 2013). The properties and chemical components of the hardening accelerator are listed in Table 2.

Fig. 1. Amorphous metallic fibers.

To investigate the flexural performance of FRC, five types of amorphous fibers in addition to hooked fibers (coming in bundles) were used. The properties of the fibers are reported in Tables 3 and 4, as declared by the producers. If the cooling rate exceeds a certain critical value, the random atomic microstructure typical of the liquid state remains "frozen" in the solid state. The atoms solidify in a non-equilibrium phase and the so-called "amorphous alloys" are obtained. Because of the different atomic microstructure compared with the so-called "crystalline alloys", completely different physical, chemical, and mechanical characteristics are obtained. Amorphous alloys have excellent strength, toughness, friction resistance, and corrosion resistance against moisture and other severe environments.

As a precondition to produce high-quality FRCs, the fibers have to be adequately dispersed. In order to evaluate the dispersibility of the amorphous fibers, a "wash" analysis of fresh AFRC was tested according to KS F2411 (2010), and its detailed process can be explained as follows. After 50 l of AFRC were mixed with an amorphous fiber volume percentage of 0.5% (=36.0 kg/m^3) based on the lab mix proportion in Table 1, 7 l of fresh AFRC was measured using a vessel to measure the air content of concrete. The measured AFRC was poured into a 0.09 mm sieve and was washed with water. The remaining materials in the sieve after washing were dried for 12 h in an oven and then all the amorphous fibers were sorted out with a magnet and weighed. The analytical washing test was repeated three times (Table 5). The average amorphous fiber volume percentage measured from 7 l fresh AFRC was found to be 0.493% (=35.5 kg/m^3) with a standard deviation of 0.00802%. This result indicates that the dispersion of AFRC is good. Using an identical mixture, a 100 × 100 × 400 mm^3 beam specimen was cast. After curing for one week, the dispersion state of the amorphous fibers within the hardened beam specimen were observed via CT (Computed Tomography) scanning at a nearby hospital. As shown in Fig. 2, the dispersibility of AFRC was generally good.

2.2. Test setup and procedure to analyze the effects of fiber properties

2.2.1. Beam specimens

To evaluate the effects of fibers properties on the flexural performance of FRC, four-point flexural tests were performed according to ASTM C1609 (2012). Three prismatic beams were cast for each variable with a cross-section of 100 × 100 mm^2 and a length of 400 mm. The prismatic beams were cured in a room at 23 ± 1 °C with a relative humidity of 60 ± 5% for the first day after concrete casting. After 1 day, all of the samples were demolded and cured