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Benefits of using amorphous metallic fibers in concrete pavement for long-term performance

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ABSTRACT

This study aims to examine the implications of amorphous metallic fibers on the mechanical and long-term properties of concrete pavement. Two different amounts of amorphous metallic fibers were incorporated into concrete, and plain concrete without fibers was also adopted as comparison. Test results indicated that the overall mechanical properties of concrete were improved by including the fibers, and the improvement increased when a higher amount of fibers was used. In particular, the equivalent flexural strength and flexural strength ratio were substantially improved by incorporating the amorphous metallic fibers. This may enable the thickness of airfield concrete pavement to decrease. The resistance to surface cracking of concrete pavement by repeated wheel loading was also improved with the addition of amorphous metallic fibers. In addition, by adding 5 kg/m^3 and 10 kg/m^3 amorphous metallic fibers in concrete pavement, roughly 1.2 times and 3.2 times longer service life was expected, respectively, as compared to their counterpart (plain concrete). Based on a life cycle cost analysis, the use of amorphous metallic fibers in concrete pavement was effective at decreasing the life cycle cost compared to plain concrete pavement, especially for severe traffic conditions.

1. Introduction

The road pavement is divided into asphalt pavement and concrete pavement according to the materials used. The former and the latter are classified as a flexible pavement and a rigid pavement, respectively, according to the stiffness of the pavement system. The use of concrete pavements has been grown over the past few decades because concrete pavements have superior durability and longer structural life than asphalt pavements, and supply and demand analysis of its material is relatively easy. In South Korea, unreinforced concrete pavement method was introduced in the 1970s, and the use of concrete pavements gradually increased after concrete pavements were first applied to NamHae expressway and 88 expressway. Nowadays, concrete pavements are widely used in expressways, and they account for nearly 16% of the total pavement area in South Korea. In addition, 30% of expressway pavements were constructed with concrete pavements in North America [1].

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Cracks in concrete pavements arise due to various reasons, and the cracks cause secondary damage such as faulting and punching. Repairing the damage is difficult and considered large scale work, so extensive studies are being performed to control the formation of cracks in concrete pavements [2]. A major cause of cracks being generated in concrete pavements is the poor tensile properties of the concrete material itself. Cracks may be an unavoidable problem in concrete pavements because plain concrete is an inherently brittle material with low tensile strength and strain capacity. Using fiber-reinforced concrete (FRC) is one way to improve this weakness of concrete. FRC is concrete made primarily of hydraulic cements, aggregates, and discrete reinforcing fibers. If properly engineered, one of the greatest benefits to using fiber reinforcement is the control of cracking and the improved long-term serviceability of the structure or product. Fibers can prevent the occurrence of large crack widths that are either unsightly or permit water and contaminants to enter, causing corrosion of the reinforcing steel or potential deterioration of the concrete. In addition to crack control and serviceability benefits, the use of fibers at high volume percentages can substantially increase the matrix tensile strength, impact strength, and flexural toughness [3]. Therefore, FRC pavements have great potential to control cracks and secondary damages, as well as reduce the required pavement thickness. The cost reduction can be as much as 12% for a 30% slab thickness reduction of concrete pavements [4].

There are numerous fiber types available for commercial and experimental use. The basic fiber categories are steel, glass, synthetic, and natural fiber materials [3]. Each fiber has its merits and faults for field applications, so users generally have multiple options. Many studies [5–11] have performed to investigate the effectiveness of using discontinuous fibers on concrete pavements. Altoubat et al. [6] experimentally examined the flexural performance of concrete pavement including synthetic and deformed steel fibers. In their study [6], several important findings were obtained: (i) by adding the discontinuous synthetic and deformed steel fibers, the flexural cracking and ultimate load capacities of plain concrete slabs were improved, and (ii) the FRCs with $R_{e,3}$ of 30% decreased the required thickness of an airfield rigid pavement by 17%. Herein, $R_{e,3} = 1000TL/3bh^2MOR \times 100\%$, where T is the toughness up to a deflection of 3 mm, L is the clear span length, b is the beam width, h is the beam height, and MOR is the flexural strength (modulus of rupture). Salemi and Behfarnia [7] evaluated the frost resistance and compressive strength of concrete pavement incorporating polypropylene (PP) fibers and nano-materials, i.e., silica and alumina. Based on their test results [7], the addition of nano-materials were more effective in improving the frost resistance of concrete pavement as compared with that of PP fibers. However, hybrid use of nano-materials and PP fibers exhibited the best performance regarding the durability, and about 87% improved durability in terms of strength was obtained in the concrete pavement by containing 5% nano-silica and 0.2% PP fibers. Li et al. [9] also investigated the abrasion resistance of concrete pavement including nano-TiO_2, nano-SiO_2, and PP fibers and concluded that the uses of nano-particles and PP fibers were efficient in improving the abrasion resistance of concrete pavement. The order of abrasion resistance was found as follows: nano-TiO_2 > nano-SiO_2 > PP fibers. Hernández-Olivares et al. [8] reported that thickness of concrete pavement is able to be reduced as roughly 5% by including 3.5 vol% recycled tyre rubber, and Nobili et al. [5] noted that the use of FRC including PP fibers can provide an efficient, safe, and cost-effective design solution for road pavement, particularly inside tunnels. Centonze et al. [11] investigated the feasibility of using recycled steel fibers from waste tires in concrete as reinforcement. By comparing the flexural performance of concrete beams and slabs incorporating recycled and industrial steel fibers, they [11] concluded that the positive effect of the recycled steel fiber on toughness was similar to that of the industrial steel fiber, but the improvement of load carrying capacity was higher for the case of industrial steel fiber as compared with its counterpart.

Lately, a new type of fiber material known as amorphous metallic fibers, which are included in the steel fiber category but have totally different mechanical properties from conventional steel fibers, was developed, and a large amount of studies on amorphous metallic fiber reinforced concrete (AFRC) have been conducted [12–15]. Amorphous metallic fibers have high tensile strength of approximately 1.4–2.0 GPa and excellent early-age crack control performance, therefore, it is expected that the crack problems in concrete pavements could be solved by using these fibers. Furthermore, amorphous metallic fibers have high corrosion resistance. One of the reasons why steel fibers are not widely used in civil or architectural structures is that steel fibers have a tendency to corrode. Although the corrosion generated in steel fibers may not adversely impact the overall performance of concrete structures, corrosion is unesthetic and would result in the slab eventually needing replacement [16].

Accordingly, this study investigated the applicability (including cost efficiency) of AFRC with a low fiber volume percentage as concrete pavements. Basic mechanical performance was tested using compressive and flexural tests, and long-term performance was tested using the small-scale accelerated pavement test. In addition, life cycle cost analysis was performed.

2. Amorphous metallic fibers

2.1. *Amorphous alloy*

When molten metal is solidified, random atomic arrangement is still remained in solid state if the cooling rate is fast enough, which is larger than the critical cooling rate. This is because atoms do not have enough time to be arranged regularly. The viscosity of the liquid metal when cooled at a faster rate than the critical cooling rate becomes larger in the supercooled liquid region, and the fluidity of the atoms in the liquid metal becomes smaller. These atoms with a smaller fluidity are solidified in the non-equilibrium phase structure and characterize a solid state [17]. Alloys that have this kind of structure are called amorphous alloys.

Amorphous alloys have an atomic arrangement consisting of short range ordering. As shown in Fig. 1, the atomic structure of amorphous alloys has a no slip system, no grain boundary, and no crystallization, so amorphous alloys have completely different physical, chemical, and mechanical