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Enhancing mechanical properties of asphalt concrete using synthetic fibers

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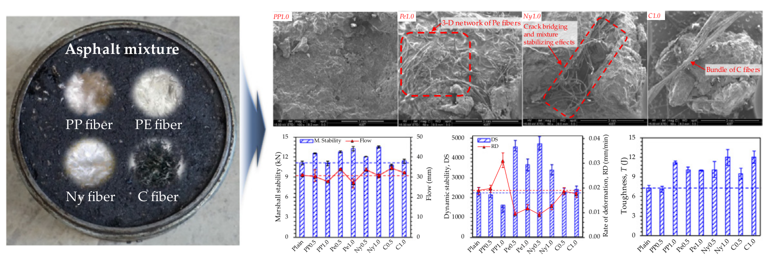
HIGHLIGHTS

- Most of polypropylene fibers are dissolved during mixing procedure due to its low melting point.
- PE and Ny fibers are most effective in improving mechanical properties of asphalt concrete.
- Reinforcing efficiency of Pe and Ny fibers is generally improved with an increase of fiber content.
- C fibers do not significantly improve most of the mechanical properties due to a bundle effect.

GRAPHICAL ABSTRACT



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ABSTRACT

This study aims to find the optimal type and concentration of fibers necessary to reinforce and enhance the mechanical properties of asphalt concrete. Four types of fibers: polypropylene (PP) and polyester (Pe) fibers with a length of 6 mm, nylon (Ny) and carbon (C) fibers, all with a length of 12 mm, were incorporated into asphalt at 0.5% and 1.0% of volume content, respectively. Six test parameters were examined for each variable to investigate the influence of the fiber type and content: the Marshall stability, porosity, indirect tensile strength, moisture susceptibility, dynamic stability, and flexural performances. Furthermore, scanning electron microscopy (SEM) images were used to accurately analyze the test results. The test results show that most of the fiber-reinforced asphalt concretes provided significantly improved mechanical performances compared to the plain asphalt concrete specimen. The optimal fiber type was the Ny fiber for every test parameter, and the optimum volume content of the Ny fiber was 1.0%, except for the case of the dynamic stability.

1. Introduction

Asphalt concrete (AC), consisting of asphalt, aggregates, and air voids, has broadly been used to produce flexible pavement due to the strong adhesion between asphalt and aggregates, which provides excellent stability and improved mechanical properties [1,2]. However, in general, great traffic loads are repetitively imposed to pavement causing distress and damages, and their impact considerably intensifies under the influence of moisture and temperature. This causes severe defects to the flexible pavement, such as asphalt draining down, fatigue cracks, and permanent deformation (rutting) [3–7]. Therefore, numerous studies have been conducted to enhance the mechanical properties of asphalt concrete, and one of the most effective methods is to incorporate fibers into asphalt concrete mixture [8–12]. The inclusion of fibers in asphalt concrete significantly reduces the draining down and leakage of asphalt by stabilizing the whole mixture [8,9]. The fibers also improve a variety of mechanical properties of asphalt

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concrete such as static and dynamic stabilities, ductility, moisture susceptibility, and general fatigue characteristics [10–12].

To date, the effects of various types and sizes of fibers, such as polypropylene (PP), polyester (Pe), nylon (Ny), carbon (C), and steel fibers on the resistance to environmental factors and the improvement of mechanical properties of asphalt concrete have been investigated [12–19]. Bueno et al. [13] reported 57% decrease in Marshall stability of asphalt concrete when 1.3% PP fibers with a length of 20 mm were included in the mixture, whereas Tapkin [12] reported 58% increase in a toughness of asphalt concrete with 2.5% PP fibers. Approximately 15% higher indirect tensile strength of asphalt concrete with 0.6% PE fibers with a length of 6 mm was obtained by a previous study [14]. They [14] also noted that toughness of asphalt concrete is improved as much as 117% by adding 0.8% PE fibers with a length of 13 mm. Kim et al. [15] experimentally verified that indirect tensile strength and Marshall stability of asphalt concrete are improved by 5% and 10%, respectively, by including 6-mm long PE fibers, and Anurag et al. [16] also reported 31% and 80% increases of indirect tensile strength and toughness of asphalt concrete, respectively, by adding 0.85% waste PE fibers with a length of 13 mm. The enhanced tensile strength and toughness of asphalt concrete by incorporating 6-mm long PE fibers were also reported by other researchers [3]. Lee et al. [17] performed the indirect tensile strength test on Ny fiber-reinforced asphalt concrete at a room temperature of 20 °C, greatly higher than the general standard test temperature. Based on their test results [17], 18% decrease and 85% increase in indirect tensile strength and fracture energy of asphalt concrete, respectively, were obtained when 1.0% Ny fibers with a length of 12 mm were added in the mixture. Likewise, although a number of studies have been carried out to improve the mechanical performance of asphalt concrete using various fibers, there is still limitation in synthesizing the test results and determining the best type and content of fiber because the earlier studies have broad variations of properties and contents of fibers and test conditions. Some researches [18,19] have also found a considerable effect of asphalt content on the mechanical properties of asphalt concrete. This definitely leads to difficult comparative analysis on the previous test results to find out the optimized fiber type and volume content.

Accordingly, to overcome the above limitation, we extensively examined the effects of four different types of fibers: PP, Pe, Ny, and C, which have been found to be the most efficient fiber types in previous studies [5–19], at two different volume fractions of 0.5% and 1.0%. Six mechanical parameters were also investigated: the Marshall stability, porosity, indirect tensile strength, moisture sensitivity, dynamic stability, and three-point flexural strength. Using this standardized approach, more reliable comparative analyses can be performed and more accurate conclusions can be drawn for the asphalt concrete mixture commercially used in South Korea. In this study, the steel fiber was eliminated from consideration, due to its inherent incompatibility with rubber tires.

2. Experimental program

2.1. Mixture proportions of the asphalt concrete

The WC-2 type of aggregate was used in this study, which is typically applied to the surface layer of asphalt pavements, and the details are described in a guide for the design and construction of asphalt mixtures [20]. This WC-2 type of aggregate is produced by mixing aggregates with a 13 mm diameter with crushed sand and filler. This mixture provides a more stable and durable macro-structure compared to other types of aggregates. Prior to mixing the aggregates, they were divided into three bins according to grading by using several sieves [21], and the result of the sieving is shown in Fig. 1. The aggregates were mixed with asphalt after they were dried at 110 °C until no variation in the weight of equal volumes was observable. The viscosity of the asphalt was kept as 170 ± 20 cSt (centistroke) and 280 ± 30 cSt during the mixing and compacting processes, respectively, and then the mixture was cured at 135 °C in a drier. Adding fibers to asphalt concrete is a process similar to adding very fine aggregate [10], and it has been known to obtain substantial benefits, such as stabilizing mixture, increasing tensile strength, strain capacity, resistance to permanent deformation [10,18,22,23]. When fibers are incorporated as a reinforcement of asphalt concrete mixture, a uniform distribution of fibers is the most important factor [24]. Therefore, after the fibers were added to the mixture, they were mixed for additional 10 min. In order to maintain the high mixing temperature of asphalt concrete mixture, a heater was used until the whole mixing process was completed, and the mixture temperature was checked using an infrared thermometer.

For the six different tests, i.e., Marshall stability, porosity, indirect tensile strength, tensile strength ratio, wheel tracking, and three-point flexural tests, two types of specimens were fabricated and tested. A more detailed explanation regarding the fabrication procedures of each specimen is introduced in the following Section 2.2. Four kinds of fibers made of PP, Pe, Ny, and C were added at concentrations of 0%, 0.5%, and 1.0% by volume to find the optimized fiber type and content. Their geometrical and physical properties were summarized in Table 1. The densities of the PP, Pe, Ny, and C fibers were approximately 0.91, 1.40, 1.14, and 1.37 g/cm^3, respectively. The PP and Pe fibers have a length of 6 mm, while the Ny and C fibers have a length of 12 mm, and their tensile strengths were 500, 1147, 800, and 4900 MPa, respectively. As mentioned earlier, the melting point of the incorporated fiber is important because the asphalt mixing temperature is as high as 160 °C. The PP fiber used in this study has a melting point of 160 °C, which is close to the mixing temperature of the asphalt concrete, while the other fibers have relatively higher melting points. The C fiber used in this study was a chopped and bundled type because each fiber had an overly small diameter of 7 μm. The asphalt content was measured as 5.34%, and every specimen was fabricated using the same mixture proportions which is one of the most broadly used asphalt concrete mixture types for the surface layer in South Korea excepting for the fiber inclusion. This was to accurately examine the influences of each fiber type on mechanical properties of asphalt concrete at the same mixture proportions.

Notation of test variables includes type of fiber and volume fraction. For example, an asphalt concrete specimen with 0.5% of the PP fibers would be notated as PP0.5 specimen, where the

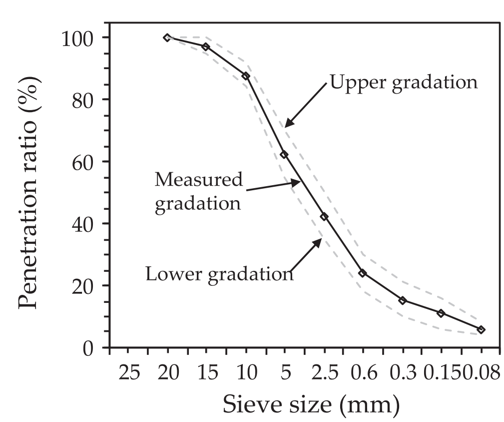

Fig. 1. Penetration ratio of aggregates according to sieve size.