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Cracking resistance of fiber reinforced asphalt concrete at −20 °C

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HIGHLIGHTS

- Proper use of steel fibers can improve the cracking resistance of asphalt concrete.
- The fiber length and diameter are critical for performance improvements in FRAC.
- Thick (0.4 mm diameter) and long (30 mm length) fibers show the best improvements.
- Additional improvement in toughness can be obtained by the deformation of fibers.
- The fiber-aggregate interlock is suggested as the fiber reinforcing mechanism in AC.

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ABSTRACT

The reinforcing effect of steel fibers in asphalt concrete is investigated through indirect tension tests conducted at −20 °C. Control specimens with no fibers, and test series with carbon and polyvinyl alcohol fibers are also carried out for comparison. Cracking resistance, indirect tensile strength, fracture energy, and post-cracking energy are obtained from the tests. The effects of fiber diameter, length, deformed shape, and content of steel fibers are investigated in order to provide fundamental understanding of the reinforcing mechanisms mobilized during fiber pull out and select proper reinforcing fibers. The test results demonstrate that the low temperature cracking resistance of asphalt concrete can be significantly improved by adding the proper type and amount of steel fibers, but that the improvements in mechanical properties are sensitive to fiber length and diameter. The indirect tensile strength and toughness of fiber reinforced asphalt concrete increase with an increase in fiber length within the 0.2–0.4 mm diameter range. Mechanical deformations of the fibers, e.g. presence of a hook or twisting, can induce further improvements in post-cracking energy absorption. Compared to unreinforced specimens, fiber reinforced specimens show up to 62.5% increase in indirect tensile strength, and up to 370% and 895% improvements in fracture energy and toughness, respectively. A hypothesis that explains the fiber reinforcing mechanism in asphalt concrete is proposed and critiqued based on the test data.

1. Introduction

1.1. Background

Fiber additives have been considered as reinforcement in composite materials including Portland cement concrete [1–3] and asphalt concrete [4–6]. In asphalt concrete (AC), fibers have been added for one of three reasons: (1) to prevent draindown or raveling of porous asphalt and stone matrix asphalt [7–10], (2) to improve resistance to cracking and rutting [11–16], and (3) to enable multifunctional applications [17–21]. While, for the first purpose, fibers are routinely used as a stabilizer, their use for the second and the third purposes is still considered in the research domain. Some recent laboratory investigations have shown that fiber additives can improve rutting and fatigue resistances [12,15], and can be used in combination with polymer modifiers [9,22–24].

Fiber reinforced asphalt concrete (FRAC) was initially tried in the field without a thorough understanding of the fiber reinforcing mechanisms [25]. Toney (1987) reported that a polyester fiber

Abbreviations: AC, asphalt concrete; FRAC, fiber reinforced asphalt concrete; ITS, indirect tensile strength; FE, fracture energy; PE, post-cracking energy; HPFRCC, high-performance fiber-reinforced cementitious composite; PVA, polyvinyl alcohol.

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(fiber length = 6.35 mm) reinforced pavement installed at the City of Tacoma showed no significant distress during four years when compared to a non-reinforced pavement [26]. Maurer and Malasheskie (1989) reported that adding polyester fibers was effective to reduce reflective cracking based on a field application at Pennsylvania Department of Transportation [27]. Huang and White (1996) also stated that FRAC containing polypropylene fibers (fiber length = 10 mm and thickness = 0.04 mm) reduced reflective cracking at Indiana [28]. Those field experiences consistently reported that, compared to regular AC, FRACs have improved resistance to fatigue, moisture damage, thermal cracking, and raveling. However, these results conflicted with some published laboratory investigations, which showed that fiber additives were not effective for improving mechanical performance. For example, while fatigue and rutting tests for FRAC showed strong improvements due to fiber addition, the tensile strength of FRAC as measured by indirect tension tests or Marshall stability tests have been generally shown to either be insignificant [14,22,29–31] or even degraded [11,32,33] as a result of adding fibers.

Recent investigations provide reasons for the contradictory observations pertaining to the fiber reinforcing effect in AC. Chen et al. (2009) showed that fiber additives require a slight increase in the optimum binder content in order to coat the surface of the added fibers [13]. They also noted that if the proper binder content is used, FRAC specimens will have higher strength than specimens without fibers. This explains the reduction in strength due to fiber addition reported by some investigators who did not adjust the binder content. Kaloush et al. (2010) showed that the strength improvement in FRAC increases with a decrease in test temperature [15]. Since cracking of asphalt pavements occurs at cold temperature, the evaluation of strength at room temperature (indirect tension test at 25 °C) or higher temperatures (Marshall stability test at 60 °C) cannot adequately capture the reinforcing effect of the fiber additives.

An interesting phenomenon showing the reinforcing effect of fibers in asphalt concrete was observed in the field test by Kutay et al. (2008). They reported that many micro cracks developed on the surface of FRAC, but they did not grow to form large alligator cracks as loading repeated [34]. In fiber reinforced cementitious concrete, the development of micro-cracks is considered to be a positive sign of proper fiber reinforcement [2]. By dispersing damage, micro-cracks retard damage localization and improve ductility.

The types of fibers that have been investigated to date are polymeric fibers (polyester, polypropylene, polyacrylonitrile), organic fibers (cellulose, lignin, date-palm, oil-palm), mineral fibers (asbestos, rock wool), waste fibers (nylon, scrap tire, textile), and other fibers (glass, carbon, steel). Organic fibers [8–9,13,24] and mineral fibers [13,24] are known to have high stabilizing effect, but low reinforcing effect. The most popular choices for reinforcing AC are polymeric fibers including polyester [8,13,22,24,26–27,34–35], polypropylene [12,27–29,32], and polyacrylonitrile [13,24]. Other fiber types tested as a reinforcement include a blend of polypropylene and aramid fibers [15,24], glass fibers [36], and waste textile fibers [9,11]. The primary purpose of adding carbon fibers [18,30,37–38] and steel fibers [16,19–21,28] are to impart electrical conductivity into AC, and their reinforcing effect is also investigated. Park (2012) [39] synthesized previous studies for various fibers, and concluded that polymeric fibers (relatively longer and thicker) are beneficial for improving rutting and cracking resistance [15,40] while organic fibers (relatively shorter and thinner) show better performance as a stabilizer [13–14,41]. Table 1 summarizes the maximum improvements of the FRACs as reported in previously published papers. The most significant improvement in mechanical response is reported by Kaloush et al. (2010); by adding 0.10% of commercial fibers by volume, they observed a 25–50% increase in indirect tensile strength (ITS) and a 50–75% increase in fracture energy (FE) at low temperature [15]. In the case of steel fibers, Serin et al. (2012) noted approximately a 20% improvement in Marshall Stability by using 60 mm long hooked fibers [16].

1.2. Objectives and Research Significance

Critical damage to asphalt concrete pavements and overlays occurs when their ambient temperature decreases significantly below freezing. This study focuses on the improvement of the cracking resistance of FRAC at a low temperature of −20 °C which is considered a reasonable representation of low field temperature. Such a temperature level occurs frequently in winter in a number of North American states and Canada. Among the various types of

Table 1
Comparison of the documented strength improvements attributed to fiber addition: only the highest improvements are selected for each publication.

Citation	Maximum improvement*				Fibers (L = length, W_f = fiber content by weight, V_f = fiber content by volume)	V_f*****	Note
	ITS**	FE***	Toughness	MS****			
Freeman et al. 1989 [35]	15%				Polyester fibers, L = 6 mm, W_f = 0.35%	0.60%	Wet ITS and wet toughness, adjusted
			117%		Polyester fibers, L = 13 mm, W_f = 0.50%	0.85%	optimum binder content
Kim et al. 1999 [22]	5%			10%	Polyester fibers, L = 6 mm	–	Dry ITS
Bueno et al. 2003 [32]				−57%	Polypropylene fibers, L = 20 mm, W_f = 0.5%	1.3%	Maximum strength reduction
Lee et al. 2005 [11]	−18%	85%			Recycled carpet (nylon) fibers, L = 12 mm, V_f = 1.0%	1.0%	Test at +20 °C
Tapkin 2008 [29]				58%	Polypropylene fibers, L = 10 mm, W_f = 1.0%	2.5%	
Li et al. 2008 [30]	28%				Carbon fibers, L = 5 mm, W_f = 0.3%, mixed with 18% graphite filler	0.38%	ITS with loading rate of 1 mm/min
Anurag et al. 2009 [40]	31%		80%		Waste polyester fibers, L = 13 mm, W_f = 0.5%	0.85%	Wet ITS and wet toughness
Chen et al. 2009 [13]				8%	Polyacrylonitrile, W_f = 0.3%	0.60%	Adjusted optimum binder content
Xu et al. 2010 [14]	8%		71%		Polyacrylonitrile, L = 5 mm, W_f = 0.3%	0.60%	Adjusted optimum binder content
Kaloush et al. 2010 [15]	49%	75%			Blend of polypropylene and aramid fibers, L = 19 mm, W_f = 0.045%	0.10%	Test at −10 °C
Serin et al. 2012 [16]				20%	Hooked steel fibers, L = 60 mm, W_f = 0.75%	0.23%	Adjusted optimum binder content
This study	**63%**	286%	727%		Hooked steel fibers, L = 30 mm, W_f = 5.0%	1.5%	Test at −20 °C
	56%	**370%**	**896%**		Twisted steel fibers, L = 30 mm, W_f = 5.0%	1.5%	Test at −20 °C

* Improvement = [(strength of FRAC/non − reinforced strength) − 1] × 100 (%).
** ITS = indirect tensile strength.
*** FE = fracture energy.
**** MS = Marshall stability.
***** Some papers describe the fiber contents in percent weight, which is converted into volume content in this table.