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Mechanical properties of roller-compacted concrete with macro-fibers

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HIGHLIGHTS

- Flexural performance of RCC and PCC with fibers was found to be similar.
- Structural performance of RCC is dependent on fiber type, geometry, and dosage.
- Synthetic fibers increased maximum dry density of RCC.
- Fracture properties of RCC were found to be similar or greater than PCC.
- Fibers maintained or increased compressive and split tensile strength of RCC.

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ABSTRACT

The addition of macro-fibers to concrete slabs on ground have been shown to increase flexural capacity, fatigue resistance, reduce crack deterioration rates, and assist in shear transfer across joints and cracks. A laboratory study was performed to determine the benefits of macro-fibers in roller-compacted concrete (RCC) for pavements by measuring the change in RCCs mechanical properties and comparing it to conventional fiber-reinforced concrete for pavements. Six fiber types, four synthetic and two steel, with several fiber geometries were incorporated into RCC mixtures at two dosage levels (0.2% and 0.4% by volume). The addition of synthetic macro-fibers increased the maximum dry density (MDD) over the control RCC mix by reducing the internal friction between aggregates whereas steel fiber had a limited impact on the MDD of RCC. For several fiber types, the resultant RCC with fibers had a statistically significant increase in compressive and split tensile strength relative to the control RCC mix. The addition of fibers did not increase the flexural strength of RCC but did noticeably improve the post-peak and residual strength capacity of RCC. The increases in residual strength were dependent on the fiber type and geometry, similar to the behavior in conventional Portland cement concrete (PCC). The fracture properties of RCC with fibers based on disk-shaped compact tension (DCT) tests were shown to be similar or greater than PCC with fibers which indicates both RCC and PCC pavements, when properly constructed, will have similar fracture and fatigue resistance.

1. Introduction

Interest in roller compacted concrete (RCC) as a paving material has increased in recent years because of its economic benefit relative to other stabilized construction materials, construction expediency, high-density paver technology, and ability to open early to traffic. From a materials perspective, RCC has reduced cementitious contents compared to typical Portland cement concrete (PCC) pavements as a result of increased aggregate content, a more continuous aggregate gradation [1,2], and increased construction compaction energy. Typical cementitious contents of RCC pavements are on the order of 12% by weight whereas those of PCC are on the order of 15%.

Due to the method of construction, RCC does not allow for the conventional placement of dowel bars. Therefore, load transfer across contraction joints in an RCC pavement may be a concern [3] especially at higher traffic levels. Structural macro-fibers may provide improved shear load transfer and residual strength in RCC as noted for conventional PCC pavement [4]. Macro-fibers have been added to PCC pavement to reduce slab thickness, control crack width and decrease crack deterioration rates, increase joint spacing, and increase fracture properties [4–8]. By reducing the crack width at a joint, the shear mechanism of aggregate interlock is enhanced [9,10], thereby increasing load transfer and potentially reducing the slabs critical tensile stresses.

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Previous studies of fiber-reinforced RCC [3,11–23] have primarily explored steel macro-fibers, with exception of one study [15] that utilized synthetic fibers. A summary of the impact of fibers on RCC mechanical properties from the literature is shown in Table 1. The addition of fibers to RCC has been shown to increase or decrease strength, elastic modulus, fracture energy, density, and fatigue life relative to RCC without fibers. Clearly, the type of fiber (steel or synthetic), geometric properties of the fiber (aspect ratio, length, shape, and surface texture), and fiber dosage affect the mechanical properties of a given fiber-reinforced concrete mixture [6,24–27]. In this study, the effect of fiber type, geometry, and dosage level on the mechanical and fracture properties of RCC will be determined for a fixed set of constituents, i.e., aggregate type and gradation; cement type and content.

2. Objectives

The addition of macro-fibers to plain concrete has provided enhanced structural and functional benefits to concrete pavements especially for concrete overlays in recent years [28]. There have been limited studies on macro-fibers, especially synthetic fibers, on the strength, toughness, and fracture properties of RCC. The objectives of this study are to characterize fiber-reinforced RCC strength, elastic modulus, fiber-reinforced concrete (FRC) toughness parameters, and disk-shaped compact tension (DCT) fracture parameters for a variety of fiber type, geometries and dosage given a fixed RCC mix design for pavements.

3. Methodology

3.1. RCC mixture design

Aggregate type and gradation is one of the key factors in the mixture design of RCC, which has been shown to impact its fresh and mechanical properties [1,2,29–31]. Three aggregate sources, coarse dolomite (19 mm nominal maximum size), dolomite chips (9.5 mm nominal maximum size), and natural sand (fineness modulus = 2.74), were proportioned to target a combined aggregate gradation that approached the 0.45 power maximum density curve. The chosen aggregate gradation has previously been shown to provide sufficient strengths for an RCC pavement with the same cement content used in this study [31]. All aggregates were sieved into individual sizes and re-combined to yield the target gradation. Aggregates were also brought to an oven-dry condition to limit between batch aggregate moisture variability.

For this study, twelve RCC mixtures (Table 2) were developed using a volumetric method: a control mixture without fibers, six mixtures with a fiber dosage of 0.4% by volume, and five mixtures with a fiber dosage of 0.2% by volume. The geometry and material properties of the six fibers are shown in Table 3. The fiber nomenclature in Table 3 uses a fiber description, e.g., surface texture or fiber feature followed by length of fiber (in mm), and fiber dosage level. For example, Emboss-48-0.4 represents a fiber with embossing, a length of 48 mm, and a dosage of 0.4% by volume. All RCC mixtures had a constant cement content of 281.8 kg/m^3 (475 lb/yd^3).

Modified Proctor tests were performed according to ASTM D1557 [32] to determine the moisture-density relationship for a given fiber type. Five point modified Proctors were performed at nominal moisture contents varying from 5% to 9% to obtain the maximum dry density (MDD) and optimum moisture content (OMC) as in listed in Table 4. Modified Proctor testing was only performed for RCC mixtures with 0.4% fiber volume. It was assumed there would be negligible difference in OMC for the lower fiber volume of 0.2%.

In general, macro-fibers produced similar or slightly greater values of OMC for the RCC mixtures, relative to the control, as shown in Table 4. The MDD of each mixture with fibers was greater than that of the RCC control mixture (see Table 4), which was also found by Neocleous et al. [16] for higher volumes of steel fibers than were used in this study. In order to determine if the fiber weight was the primary reason for the increased MDD, the weight of fibers per cubic meter of RCC was subtracted from the MDD as shown in Table 4. The results in Table 4 clearly demonstrate that addition of any synthetic macro-fiber aided in compaction of the RCC, whereas steel fibers had only a limited impact on the MDD, i.e., Helical-25 and Hook-60. On average, synthetic fiber mixes increased the MDD by 55 kg/m^3 or 2.3% relative to the control mixture, whereas steel fibers only increased the MDD by 11 kg/m^3 or 0.5%. The proposed mechanism for the increased MDD in RCC containing synthetic fibers was a reduction in the internal friction between the aggregates provided by the polymeric fiber.

3.2. Specimen mixing, fabrication, and testing

All specimens were mixed in a pan mixer according to ASTM C192 [33] using the final mixture proportions in Table 2 and were moist cured in a fog room until testing. Similar to conventional PCC, fibers in RCC must be added at the right time and with sufficient shearing in the mixer for adequate dispersal, else fiber balling may occur. The fibers and dosages used in this study did not have a noticeable impact on the RCC workability. For compressive, split tensile, and elastic modulus testing, 100 by 200 mm cylinders were compacted with a vibratory hammer similar to ASTM C1435 [34] with the differences being the size of the tamping plate (88 mm diameter), number of lifts (three), and cylinder size (100 by 200 mm versus 150 by 300 mm). Three replicate cylinders were made for each strength and modulus test. Elastic modulus, com-

Table 1
Effects of fibers on RCC mechanical properties relative to non-fiber reinforced RCC from literature (values indicate volume dosage of fibers used in study).

	Increase	No effect	Decrease	Variable
Split tensile strength	Nanni [3] – 0.58%; Kokubun [14] – 0.25, 0.5, 0.75%			Sobhan [19] – 0.25 and 0.5%
Compressive strength	Nanni [3] – 0.58%; Muscalu [21] – 3%; Madhkhan [15] – 0.4, 0.6, 0.8% (steel) nd 0.1% synthetic	Kokubun [14] – 0.25, 0.5, 0.75%	Sobhan [19] – 0.25 and 0.5%; Neocleous [16] – 1 and 2%	
Elastic modulus	Nanni [3] – 0.58%		Muscalu [21] – 3%	
Flexural strength	Kokubun [14] – 0.5 and 0.75%; Muscalu [21] – 3%		Kokubun [14] – 0.25%	Sobhan [19] – 0.25 and 0.5%; Madhkhan [15] – 0.4, 0.6, 0.8% (steel) and 0.1% synthetic
Fatigue life	Graeff [13] – 2 and 6% for stress ratios <0.7		Graeff [13] – 2 and 6% for stress ratios >0.7	
Fracture energy	Yandong [20] – 0.5 and 1%			
Maximum dry density	Neocleous [16] – 1 and 2%	Nanni [3] – 0.58%		