Enhancement of Rigid Pavement Capacity Using Synthetic Discrete Fibers

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Abstract. Adding synthetic discrete fibers to unreinforced rigid pavements has been significantly increased during the last decades. Synthetic fibers improve flexural capacity, toughness, fatigue resistance, and durability, and reduce crack width. Most design methods of rigid pavements adopted modulus of rupture (i.e., flexural strength) as the primary parameter in the input design process. The elastic modulus of rupture, which has calculated depending on ASTM C78 formula does not reflect the benefits of the synthetic fiber. The effective modulus of rupture (MOR’) has been proposed to quantify the added capacity of fibers over unreinforced concrete, which is calculated depending on the equivalent flexural strength. This study aimed to determine the flexural capacity of rigid pavement, which included filtrated polypropylene discrete fibers. The concept of the effective modulus of rupture was adopted to calculate the capacity of rigid pavements. Adding Polypropylene in concrete reduced the compressive strength, modulus of elasticity, elastic modulus of rupture, while improves effective modulus of rupture and flexural toughness.

1. Introduction
Although the rigid pavements are more expensive than flexible pavements, it has longer service duration and lowers required maintenance process [1, 2]. The design purpose of rigid pavements is to provide enough reinforcement to control cracks, which are generated from applied traffic load and environment variation [3]. Therefore, over several decades welded steel meshes have been utilized as a traditional option for the reinforcement of slabs on the ground or rigid pavements. Last three decades, the utilize of discrete fibers in concrete pavements has increased. Adding any discrete fibers to concrete does not prevent cracks appearance but delay the amount and intensity of cracks [4]. Fiber-reinforced concrete (FRC) has been widely utilized to improve the performance of unreinforced concrete and uses in new infrastructure, rehabilitation, repair, and retrofits. FRC is a composite mixture composed of discrete fibers and concrete matrix, which composed of cement, sand, aggregates, and additives. Discrete fibers can significantly improve flexural performance, impact resistance, fatigue properties, shrinkage resistance, and ductility, and decrease width and intensity of cracks [5, 6, 7, 8, 9, 10, 11].
The primary role of discrete fibers is bridging forces across initiated cracks due to distributing within a concrete matrix, which leads to make these cracks closer together [12, 13, 14, 15]. According to several experimental works of rigid pavements or slabs on ground, discrete fibers improve slab capacity, toughness, and reflective cracking resistance, and reduce the cracks width and the required slab thickness [12, 16, 17]. Two main factors control of FRC performance, type and amount content of discrete fiber. Each fiber kind with specific content has a specific behavior within a concrete matrix that is different from other concrete matrix or fiber kind. Fiber amount contributes to determining the fiber role within the concrete matrix that is ranged from few amounts (0.01%) to high amount (3%) [18, 19]. Steel fibers have a successful history in paving applications, but over the last two decades synthetic fibers have become predominant due to their lightweight, low cost, and resistance to rust damage [12, 20]. Synthetic fibers are human-made fibers resulting from petrochemical processes [21]. There are many synthetic fibers types have been used in concrete applications such as acrylic, aramid, carbon, nylon, polyester, polyethylene, polyvinyl alcohol (PVA) and polypropylene. Synthetic fibers have high elongation properties, low density, and low modulus of elasticity [22]. Polypropylene (PP) is the most common type used for concrete pavements applications [23, 24]. Polypropylene is available in two kinds, monofilament polypropylene (FPP) and fibrillated polypropylene (MPP) [25]. FPP is microfiber (length <25 mm) and is effective within the concrete matrix mechanically (not chemically) by a cohesive mechanism [26]. FPP fibers improve the properties of the plastic concrete stage by increasing the homogeneity of the mixture. Also, they decrease the bleeding rate and plastic settlement [25]. FPP fibers have adverse or little effect on mechanical properties of concrete such as compressive strength, modulus of elasticity, and flexural strength (modulus of rupture). On the other hand, flexural toughness has been significantly increased by adding FPP fibers.

2. Rigid Pavement Capacity

Many testing approaches have been proposed to determine several properties of FRC including compression, tension, shear, and bending tests. All design methods of rigid pavement have been adopted used the flexural strength (i.e., modulus of rupture) to determine the flexural capacity of pavement, which calculated depending on ASTM C78 formula. Moreover, adding synthetic fibers to concrete does not improve the mechanical properties like a modulus of rupture (MOR) especially for synthetic microfibers [27, 28, 29, 30]. Hence, using the elastic formula of ASTM C78, 2010 [31] does not reflect the benefits of the fiber [32, 33, 34]. Therefore, Moens and Nemegeer [50] first recommended the post-cracking concept (toughness) to take into account the benefits of the discrete fiber in the concrete slab on the ground. Altoubat et al. [33] proposed using the equivalent flexural strength ratio (Re,3) to quantify the added flexural capacity of discrete fibers over unreinforced concrete. Re,3 is defined as the ratio between the equivalent flexural strength (fe,3) value and the elastic modulus of rupture (MOR). They also used an effective modulus of rupture (MOR') to determine the slab capacity, which presents a percentage increase to the (MOR). The fe,3, Re,3, MOR, and MOR’ are calculated as follows:

\[
\text{MOR} = \frac{PL}{bd^2} \quad (1)
\]
\[
fe,3 = \frac{TL}{3bd^2} \quad (2)
\]
\[
Re,3 = \frac{fe,3}{MOR} \quad (3)
\]
\[
\text{MOR'} = \frac{fe,3}{MOR} \quad (4)
\]

Where \(\text{MOR}\) is the modulus of rupture (MPa), \(fe,3\) is the equivalent flexural strength (MPa), \(Re,3\) is the equivalent flexural strength ratio (%), \(MOR'\) is an effective modulus of rupture (MPa), \(P\) is the maximum flexural load recorded (N), \(T\) is the area under load-deflection curve up to an ultimate point (Joule), \(L\) is the beam span (mm), \(b\) is the beam width (mm), and \(d\) is the beam depth (mm).
3. Aim of the Study
This research aimed to determine the flexural capacity of rigid pavement, which included filtrated polypropylene discrete fibers. The concept of the effective modulus of rupture was adopted to calculate the capacity of rigid pavements.

4. Experimental Work
In this study, Type I/II ordinary Portland cement of ASTM C150 [36] with a specific gravity of 3.15 was used. Natural fine sand with a specific gravity of 2.63 was used. A crushed limestone with a maximum size of 19 mm was used as coarse aggregate for all mixtures. Both coarse and fine aggregates conformed to the ASTM C33 [37] specification. All FRC mixtures had the same water-cement ratio (w/c) of 0.45. Fibrillated polypropylene (FPP) discrete fibers were used in this study and added with different contents. The length and diameter of FPP were 38 and 0.9 mm, respectively. FPP had 1138 MPa in tensile strength and 7.8 in specific gravity. The mixing procedure involved mixing the coarse and fine aggregates in the mixer for 1 minute. Portland cement was added then to the mixer, and all the materials were dry-mixed for more 1 minute. FPP was spread into the mixture, and the materials were mixed again for 2 minutes. Finally, superplasticizer was poured into the total amount of water outside the mixer, and the solution was added gradually and mixed for 2 minutes. For compressive strength specimens, the concrete mixture was placed in the plastic cylinder molds in two layers and vibrated for 30 seconds. For flexural testing, the mix was cast using in steel prism mold in two later a and vibrated for 1 minute. All cylinders and prisms samples were stored in a water tank saturated for 27 days. All compressive and flexural tests were tested at 28 days. Table 1 presents the mix proportions.

| Case   | Cement | Aggregates | Sand | Water | Polypropylene |
|--------|--------|------------|------|-------|---------------|
| Plain1 | 12.8   | 40.1       | 28.0 | 18.1  | 0             |
| 0.5PFRC| 12.7   | 39.9       | 27.9 | 18.0  | 0.5           |
| 0.8PFRC| 12.6   | 39.7       | 27.9 | 17.9  | 0.8           |
| Plain2 | 29.2   | 0          | 33.0 | 36.8  | 0             |
| 1.5PFRCC| 28.7 | 0          | 32.5 | 36.3  | 1.5           |
| 2PFRCC | 28.6   | 0          | 32.3 | 36.1  | 2.0           |

5. Results and Discussion

5.1. Compressive Strength
Figure 1 shows the compressive strength results for plain, PFRC, and PFRCC. The plain mixture showed the highest compressive strength compared with all FRC mixtures. PP fibers had a little adverse effect on the compressive strength especially for concrete mixtures without aggregates (PFRCC). Figure 2 shows that PP reduced modulus of elasticity with increase dosage amount. The results of compressive parameters agree with previous studies [17, 19, 38]. On the other hand, PP fibers had a significant effect on the failure mode of the compressive failure from brittle to ductile mode.
5.2. Flexural Strength

Load-deflection curve, which calculated based on the average value from two LVDTs for all the specimens are shown in Figure 3. These load-deflection curves were utilized to calculate all flexural parameters such as modulus of rupture (MOR), residual strength, (R150), effective modulus of rupture (MOR’), and flexural toughness. From Figure 3, polypropylene fiber improves the flexural deflection at failure significantly by more than 25 times of plain mix. All FRC exhibits drop loading which immediately occurs when a plastic hinge was formed. The PFRC mix showed a highly drop in load after peak point by more than 90%, while the PFRCC mix dropped by 50%. The peak load for PFRC mixtures was higher than PFRCC mixtures due to the effect of aggregates in mixtures.
The results of the tests for flexural capacity (elastic modulus of rupture and effective modulus of rupture) are given in Figure 4. It was observed that elastic modulus of rupture (MOR) decreases with increasing PP content, while effective modulus of rupture increases with the same PP content. Therefore, using the residual strength concept to determine the flexural capacity of FRC reflects the fibers benefits. Figure 5 shows the flexural toughness of plain, PFRC, and PFRCC mixture. The incorporation of PP fibers improved the flexural toughness by 20 times of plain concrete.
6. Conclusion

Based on the results of the experimental work, the following conclusions can be drawn:

1. The value of the compressive strength and modulus of elasticity decreased by adding polypropylene fibers in concrete, especially for the concrete mix without aggregates.

2. The mode of compressive failure was changed from a brittle to a ductile failure by adding polypropylene in concrete.

3. The addition of polypropylene fibers had decreased the modulus of rupture, which is calculated based on ASTM formula. The obtained results indicated that the use of 0.5, 0.8, 1.5, and 2.0% PFRC led in 6, 18, 27, and 37% reduce in MOR, respectively, especially for a concrete mix without aggregates.

4. Results of flexural toughness showed that PFRC samples acquire a high flexural toughness compared to plain concrete samples.

5. Effective modulus of rupture had significantly improved by adding polypropylene fibers in concrete. Adding 0.5, 0.8, 1.5, and 2.0% polypropylene fibers in concrete increased the MOReff. by more than 8, 11, 12, 18%, respectively.

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