Analysis of Flexural Capacity of Fiber Reinforced Concrete Pavements

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Abstract: The utilization of concrete pavements has been grown over the last decades because it has high durability and longer structural life compared with asphalt pavements. Cracks in concrete pavements present the main factor of pavement failure, and the major cause of appear cracks is the weak tensile and flexure properties of the concrete material itself. Therefore, utilizing discrete fiber in concrete is one option to decrease the weakness of concrete. This paper using the cylinder and beam specimens to understand the effect of two different types of discrete fibers and various volume on mechanical properties of concrete. Additionally, the expermental results were simulated by Finite Elements Method (FEM) through ANSYS software program. The mechanical properties for seven cases used in this study related to Fiber Reinforced Concrete (FRC) included compressive strength, modulus of elasticity, break strength, modulus of rupture, and flexural toughness. The outcome of the study indicated that low volume fraction of the steel and Polyvinyl Alcohol (PVA) fibers have little effect on the flexural capacity of concrete pavement, but steel fibers provide improvements that are more significant in toughness and residual strength than PVA fibers. Adding 0.4 and 0.6% steel fibers to concrete pavement provided flexural toughness up to 82 and 94 N.m, which is about 137 and 156 times, respectively. The analytical analysis by ANSYS software provided results which are close to experimental work with more safer design.

Keywords: Concrete pavement, FRC, steel fiber, PVA fiber, modulus of rupture

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I. INTRODUCTION

Pavements are usually either asphalt or concrete type, and it is playing significant to transmit the applied loads to the foundation. In recent decades, concrete pavements are preferred because of their low life-cycle cost, durability and low maintenance. Typically, concrete pavements are a better alternative to asphalt pavements for a highway under high traffic loads [1]. The concrete material is considered a high strength in compression and a weak in tension. Therefore, it needs to
improve its performance in tension and flexure states. FRC fibers improve tension and flexural capacity of concrete by increasing toughness and ductility and controlling crack width [2, 3, 4, 5, 6, 7, 8]. In pavements or slabs on ground applications, discrete fibers have been used for several decades because of its increased ultimate capacity, toughness, load transfer efficiency at cracks, and decrease the crack width [9, 10, 11, 12, 13, 14].

Steel discrete fiber the most common fiber type, has been used in concrete applications and the amount has been utilized range of (0.2-2.0%) [15] typically. Steel fibers have been used within several concrete applications such as pavements, slabs, columns, bridge decks, boxes, tanks, industrial floors, and repair techniques [16, 17, 18].

Synthetic fibers are human-made fibers resulting from several processes and development in the petrochemical field and textile industries. Synthetic fiber types, which have been used in concrete applications, are acrylic, aramid, carbon, nylon, polyester, polyethylene, and polypropylene [19, 20]. Among the many kinds of discrete synthetic fibers utilized in concrete applications, PVA fiber is a relatively new inclusion. PVA is developed by polyvinyl acetate that is hydrolyzed by treating an alcoholic solution with aqueous acid [21, 22]. This study aims to determine the flexural capacity of concrete pavements with different content of PVA or steel discrete fibers. Also, simulation of the excremental results by FEM through using ANSYS software program.

II. BEHAVIOR OF FRC

The FRC response under compressive stress, which is prepared from the compressive test, shown in Fig. 1a. The first portion of the curve presents the elastic stage, and the slope of that portion presents the modulus of elasticity (E). The peak point of the curve presents the compression strength of concrete (fc’) and peak strain (εc). The end of the curve presents the break strength and ultimate strain at failure (εu). The FRC response under flexural stress is shown in Fig. 1b. The first flexural parameter is the flexural capacity, which is called the Modulus of Rupture (MOR). MOR presents a primary design input and is the maximum strength of concrete before the failure happens. The second flexural property is the Flexural Toughness (FT), which is concrete’s ability to absorb energy and plastically deform without fracturing. The concrete’s toughness is a very important characteristic for all concrete mixtures, which are increased significantly by adding fibers. Even though toughness is not a design parameter, it indicates useful data since it contributes to load transfer across cracks. All those parameters determine as explained in the testing procedure sections.

III. ANALYTICAL ANALYSIS

Concrete is composed of inhomogeneous and anisotropic materials; therefore, it is complicated to model. In this study, ANSYS 14 workbench [23] is used to simulate the experimental works. Solid65 is used for the 3-D modeling of solids with or without reinforcing bars (rebar) and reinforced composites. The solid has the capability of cracking in tension and crushing in compression. The element has eight nodes with having three degrees of freedom at each node. Also, there are translations in the nodal x, y, and z directions.

IV. EXPERIMENTAL PROGRAM

A. Testing Procedures

The experimental testing program involved performing three different tests for seven cases of concrete mixtures, including [24, 25, 26, 27]. Table 1 summarizes laboratory testing methods, and types and sizes of testing specimens utilized in the experimental work.
TABLE 1
SUMMARY OF EXPERIMENTAL TESTING METHODS AND SPECIMENS

<table>
<thead>
<tr>
<th>Testing Type</th>
<th>Testing Methods</th>
<th>Dimensions (mm)</th>
<th>Calculated Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive Strength</td>
<td>ASTM C39</td>
<td>Cylinder (100×200)</td>
<td>Compression Strength (fc')</td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>ASTM C469</td>
<td>Cylinder (100×200)</td>
<td>Modulus of Elasticity (E)</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>ASTM C78</td>
<td>Prism (150×150×560)</td>
<td>MOR</td>
</tr>
<tr>
<td>Flexural Performance</td>
<td>ASTM C1609</td>
<td>Prism (150×150×560)</td>
<td>FT</td>
</tr>
</tbody>
</table>

B. Materials Properties

Seven different mixtures consisted of cement, sand, aggregate, water, and discrete fibers as shown in Table 2. All mixtures had the same water-to-cement (w/c) ratio of 0.45, and the maximum aggregate size was 19.0 mm. The properties of PVA and steel discrete fibers were used in the experimental work listed in Table 3.

TABLE 2
SUMMARY OF MIX PROPORTIONS (% BY VOLUME).

<table>
<thead>
<tr>
<th>Case</th>
<th>Cement</th>
<th>Water</th>
<th>Sand</th>
<th>Aggregate</th>
<th>Fiber (P: PVA &amp; S: Steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>12.8</td>
<td>18.1</td>
<td>28.0</td>
<td>40.1</td>
<td>0</td>
</tr>
<tr>
<td>0.1% PVAFRC</td>
<td>12.8</td>
<td>18.1</td>
<td>27.0</td>
<td>40.0</td>
<td>0.04P</td>
</tr>
<tr>
<td>0.3% PVAFRC</td>
<td>12.7</td>
<td>18.0</td>
<td>27.9</td>
<td>39.9</td>
<td>0.12P</td>
</tr>
<tr>
<td>0.5% PVAFRC</td>
<td>12.7</td>
<td>18.0</td>
<td>27.9</td>
<td>39.9</td>
<td>0.2P</td>
</tr>
<tr>
<td>0.75% SFRC</td>
<td>12.7</td>
<td>18.1</td>
<td>27.9</td>
<td>39.9</td>
<td>0.3S</td>
</tr>
<tr>
<td>1.0% SFRC</td>
<td>12.7</td>
<td>18.0</td>
<td>27.8</td>
<td>39.7</td>
<td>0.4S</td>
</tr>
<tr>
<td>1.5% SFRC</td>
<td>12.6</td>
<td>17.9</td>
<td>27.8</td>
<td>39.4</td>
<td>0.6S</td>
</tr>
</tbody>
</table>

TABLE 3
PROPERTIES OF DISCRETE FIBBERS

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Configuration</th>
<th>Specific Gravity</th>
<th>Length, mm.</th>
<th>Diameter, mm.</th>
<th>Tensile Strength, MPa</th>
<th>Flexural Strength, GPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVA</td>
<td>Monofilament</td>
<td>1.3</td>
<td>0.25</td>
<td>0.001</td>
<td>1655</td>
<td>38</td>
</tr>
<tr>
<td>Steel</td>
<td>Mono Cold Drawn</td>
<td>7.8</td>
<td>1.5</td>
<td>0.035</td>
<td>1138</td>
<td>200</td>
</tr>
</tbody>
</table>

V. RESULTS OF EXCREMENTAL WORKS

A. Results of Compression Tests

Fig. 2 shows the compression strength of plain, PVAFRC, and SFRC. For both fibers, the general trend of the compression strength shows an increase in its value with the increase of the fiber dosage. The addition of the PVA fibers to concrete increases the compression strength by more than 9, 12, and 15% at 0.04, 0.12, and 0.2% contents, respectively. Steel fibers also improve compression strength by more than 23, 30, and 41% at 0.3, 0.4, and 0.6% contents, respectively.

Fig. 2. Effect of fiber content on compressive strength of concrete
Fig. 3 shows the modulus of elasticity of plain, PVA FRC, and steel FRC as a function of fiber content. From the Figure, it is noticeable that the addition of the fibers to concrete decreased the modulus of elasticity of the concrete. There was no specific correlation between fiber dosage and the modulus of elasticity. All the results of compressive strength and modulus of elasticity agreed with results of the study of [28]. Fig. 4 shows the effect of discrete fiber on the break strength. The addition of PVA and steel fibers slightly increased the break strength of the plain concrete, which led to preventing the sudden failure of concrete structures.

![Fig. 3. Effect of fiber content on modulus of elasticity of concrete](image1)

![Fig. 4. Effect of fiber content on compressive strength of concrete](image2)

The impact of type and content of discrete fiber on the stress-strain curve of the concrete under compression stress are shown in Figures 5 and 6. Clearly, adding fiber to plain concrete changes failure response from brittle to ductile. Adding 0.2% PVA increases the ultimate strain by more than 40%. Using 0.6% steel fibers within concrete includes improved the ultimate strain by more than 60%.

![Fig. 5. Compressive stress-strain curve of PVAFRC](image3)
B. Results of Flexural Tests

The impact of the content of each fiber type on flexural properties of concrete has been found to correlate very well with the results of the experimental work presented. Fig. 7 and 8 summarize the load-deflection data of the flexural test of plain, PVA FRC, and steel FRC, which were used to determine the flexural parameters. It is noted that increasing fiber content improved the state of concrete failure from brittle to ductile material. Furthermore, the steel fibers improve concrete ductility of plain concrete more than PVA.

The results of the flexural capacity are presented in Fig. 9. Clearly, discrete fibers have been found to have little impact on flexural capacity since the fiber role starts after concrete matrix cracks, which does not take into account of the formula of MOR. Fig. 10 shows the flexural toughness results, which were conducted from the
load-deflection curve of FRC under flexural stress. All fiber types and dosages more than 0.3% increase the FT when compared to the plain concrete, but the degree of improvement varied significantly. Adding 1.0 and 1.5% steel fiber increased the flexural toughness of plain concrete by factors of 137 and 156 times, respectively.

![Graph of flexural capacity vs fiber content](image1)

**Fig. 9.** The flexural capacity of FRC

![Graph of flexural toughness vs fiber content](image2)

**Fig. 10.** The flexural capacity toughness of FRC

**VI. RESULTS OF ANALYTICAL WORKS ANALYSIS**

In this section, a non-linear FEM by incorporating the maximum tensile stress and maximum displacement of the plain, PVAFRC, SRFC obtained was developed to compare the results of experimental works with FEM results as shown in Table 4. Figures 11 and 12 show the analytical analysis of the experimental work by ANSYS. From these results, it was noted that the maximum computed tensile stresses and maximum displacements using FEM tend to underestimate the actual stress.

![ANSYS results of PVAFRC](image3)

**Fig. 11.** ANSYS results of PVAFRC, a. Deformation, and b. Stress.
TABLE 4
COMPARISON BETWEEN EXPERIMENTAL AND ANALYTICAL WORKS

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Displacement, mm</th>
<th>Max. Tensile Stress, Mpa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ANSYS</td>
<td>Experimental</td>
</tr>
<tr>
<td>PVA</td>
<td>0.59</td>
<td>0.66</td>
</tr>
<tr>
<td>Steel</td>
<td>1.37</td>
<td>1.70</td>
</tr>
</tbody>
</table>

VII. CONCLUSION

Based on the observed test results, the following conclusions can be drawn:

1. Fiber type and content have a significant effect on compressive strength, compressive break strength, flexural toughness, and flexural deflection of FRC.

2. Steel fibers provide more significant improvements in toughness and residual strength than synthetic fibers, and both parameters are proportional to dosage rate for any fiber used.

3. Steel and PVA discrete fibers have been found to have little effect on flexural capacity (modulus of rupture) of concrete.

4. Flexural toughness presents a good indicator of the improved flexural performance of FCR.

5. Adding 0.4 and 0.6% steel fibers to concrete provided flexural toughness up to 82 and 94 N.m, which is about 137 and 156 times, receptively.

6. The analytical analysis by ANSYS software provided underestimate the actual tensile stresses and displacements.

REFERENCES


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