Characterization and performance of high performance concrete for pavements

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Abstract

Several states in the U.S. are undertaking a variety of innovative research in high performance concrete pavement materials and innovative design/construction features. This paper addresses the investigation undertaken in exploring the use of fiber reinforced and low shrinkage concrete in pavements. Past experience with these materials have indicated i) potential benefits in flexural fatigue resistance and reduction in crack development, and ii) potential reduction in slab warping effects with implications on pavement slab longevity. The objective of this study was to examine the design and lab performance of these materials for local conditions in Maryland, monitor their lab and field performance, and quantify potential benefits. This paper presents the laboratory shrinkage, toughness, and fatigue analysis results for mixtures used in the construction of a major highway artery in Route 50 in Maryland.

Keywords: high performance concrete, fiber reinforced concrete, fatigue, shrinkage, toughness.

1 Introduction

Over the years, in order to increase concrete's flexural behavior, ductility and energy absorption, fiber reinforced concrete (FRC) has been introduced. In fiber reinforced concrete, fibers are introduced into the concrete as it is mixed. These fibers are dispersed randomly throughout the concrete and thus improve concrete properties. Other advantages include the increase in tensile strength, fatigue strength, and impact strength. [1, 2, 3, 4]. In terms of shrinkage, several parameters affect this property including material properties, mixture composition, temperature and relative humidity of the environment, the age of
the concrete, and the size of the structure [6, 7, 8]. When concrete is restrained from shrinking, tensile stresses may develop and if tensile stresses go beyond the tensile strength concrete may start to crack. Cracking is a major concern in highway pavements and the use of short, randomly distributed fibers in fiber reinforced concrete may actually reduce shrinkage cracking [9].

In this study the laboratory evaluation included both fiber reinforced and low shrinkage concrete mixtures [10, 11]. Specifically, the MD Mix 7, used for highway pavements in Maryland, was the control mix. This study examined the effects of fiber content (ranging from 0.1% - to 0.4%) on concrete properties. The research team selected a candidate polypropylene fiber for the laboratory testing. According to the recommendations of the industry and the project advisory panel, the low shrinkage concrete was based on the use of MD #357 aggregate in place of the #57 aggregate, and/or modifying the w/c ratio.

Unrestrained shrinkage of hardened concrete was evaluating with ASTM C 157, while Flexural Strength & Toughness was tested according to ASTM C-78 and ASTM C1018. For fatigue testing and endurance a cyclic load was used with a close loop testing apparatus and Stress Ratio of 0.49, 0.59, 0.69. The endurance limits were evaluated at 2 million cycles and with 20 cycle per second loading.

2 Experimental results

The shrinkage testing results are shown in Table 1. The Low Shrinkage mixture with reduced w/c ratio (#57LS) had low shrinkage than the one with large size aggregate (#357LS). Shrinkage of the control concrete was very close to the one of the low shrinkage mixtures, while the fiber mixtures has higher shrinkage.

<table>
<thead>
<tr>
<th>Aggregate Type</th>
<th>(%) Fiber</th>
<th>Length Change Average (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#57</td>
<td>0.0</td>
<td>-0.018</td>
</tr>
<tr>
<td>#357</td>
<td>0.1</td>
<td>-0.040</td>
</tr>
<tr>
<td>#357</td>
<td>0.2</td>
<td>-0.047</td>
</tr>
<tr>
<td>#357</td>
<td>0.3</td>
<td>-0.035</td>
</tr>
<tr>
<td>#357</td>
<td>0.4</td>
<td>-0.044</td>
</tr>
<tr>
<td>#57 LS</td>
<td>0.0</td>
<td>-0.024</td>
</tr>
<tr>
<td>#57 LS</td>
<td>0.0</td>
<td>-0.013</td>
</tr>
</tbody>
</table>

The toughness results are shown in Table 2. In this table the average values of the toughness indices are presented. The indices were obtained from the stress strain diagram, an example is shown in Figure 1, using the definitions and testing
conditions of ASTM 1018. Plain concrete failed immediately upon cracking, and thus toughness indices $I_5$, $I_{10}$, and $I_{30}$ are always equal to 1. Fiber reinforced concrete carried loads after the first crack into the plastic zone. Ductility and energy capacity was increased with adding fibers. As it can be seen from Table 2, the 0.3% and 0.4% fiber reinforced concrete mixtures showed the highest toughness results, 5.5 and 5.6 respectively for the $I_{20}$ index for example.

![Graph](image)

Figure 1: Toughness testing result for 0.2% Fiber Reinforced Concrete.

Table 2: Toughness indexes.

<table>
<thead>
<tr>
<th>Fiber (%)</th>
<th>$I_5$</th>
<th>$I_{10}$</th>
<th>$I_{20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Toughness Index</td>
<td>Toughness Index</td>
<td>Toughness Index</td>
</tr>
<tr>
<td>0.1</td>
<td>2.6</td>
<td>3.0</td>
<td>3.3</td>
</tr>
<tr>
<td>0.2</td>
<td>3.2</td>
<td>3.5</td>
<td>4.0</td>
</tr>
<tr>
<td>0.3</td>
<td>3.3</td>
<td>4.1</td>
<td>5.5</td>
</tr>
<tr>
<td>0.4</td>
<td>3.2</td>
<td>4.2</td>
<td>5.6</td>
</tr>
</tbody>
</table>

In order to evaluate the effects of fibrillated polypropylene FRC on fatigue and evaluate potential benefits as compared to conventional concrete, beams with plain concrete and fiber reinforced concrete with 0.1 %, 0.2 %, 0.3 % and 0.4 % fibers were prepared and tested in flexural fatigue. At least three replicates were tested at each stress level of 0.49, 0.59, and 0.69 and several batches were
included in the study since fatigue data typically present high variability. While individual mixture “Flexural Fatigue Stress versus Number of Cycles” (FFS-N) curves were created the combined graphs are shown in Figure 2. In this graph, the 0.1 % fiber reinforced concrete provides an advantage, in terms of fatigue over the remaining mixtures. Because the 2 million cycle limit is chosen to approximate the life span of a structure that may typically be subjected to fatigue loading, such as a bridge deck or a highway pavement, from Figure 2 it can be observed that at 2 million cycles the corresponding flexural fatigue stress for the 0.1%, 0.2%, 0.3% and 0.4% FRC concrete was in the order of 3999 kPa (580 psi), 3792 kPa (550 psi), 3654 kPa (530 psi), 3516 kPa (510 psi). This indicates that the 0.1% fiber reinforced concrete provides a higher fatigue performance among the remaining mixtures.

![Figure 2: FFS-N for Concrete Mixtures.](image)

**Figure 2:** FFS-N for Concrete Mixtures.* PL = Plain Concrete, 1F = 0.1% Fiber Reinforced Concrete, 2F = 0.2% Fiber Reinforced Concrete. Units : 100 Psi = 0.69 mPa.

### 3 Fatigue models

Fatigue models were developed based on regression analysis from the above data. The linear relationship was used for stress levels between 0.49 and 0.69. The fatigue testing of 0.49 stress level with plain concrete and 0.1%, 0.2%, 0.4% fiber reinforced concrete exceeded 2.5 million cycles without significant damage. According to PCA (Portland Concrete Association) when the stress level is not more than about 0.55, concrete will withstand virtually infinite number of load repetitions.
As an example of these models the relationship of flexural fatigue stress versus number of cycles (LOG $N_f$) for plain concrete is presented. Such a relationship had a 0.93 coefficient of correlation. The linear fatigue model was thus as follows:

$$\text{Log} (N_f) = 1298 - 53 f_c$$

where, $f_c$ = flexural fatigue stress (PSI) = Stress Level * MOR, and $N_f$ = number of failure cycles.

Similarly for the 0.2 % fiber reinforced concrete such a relationship had a 0.94 coefficient of correlation. The fatigue model obtained was:

$$\text{Log} (N_f) = 1083 - 36 f_c$$

Such models are clearly valid for stress levels between 0.59 and 0.69 and should be further calibrated when mixtures with different characteristics are considered.

Multiple regression was used to examine potential effects of mix properties and fiber content on fatigue. The linear form of the model for multiple regression was:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k + \varepsilon$$

where $y$ is dependent variable, $x_1 \ldots x_i$ are independent variables and $\beta_0 \ldots \beta_i$ are experimental coefficients of the regression model. F test and T test were used to test the validity of the models and testing the coefficients of the multiple regression models with 95% significance.

While several models were examined it was found out that combining conventional concrete and fiber reinforced concrete fatigue data did not provide acceptable models. In this effort the only independent variable that was significant was the applied stress level. In the next step, only fiber reinforced data were considered. For this model a value of 0.784 for $R^2$ was obtained, indicating that 78.4 percent of the variation was explained by the linear regression model. According to the F and T tests in the multiple regression analysis, the model is able to represent the data (Significant F < 0.05; f theoretical equal to 9.345, $f > F_{0.05,5,23} = 2.44$), and all the variables are significant except Fiber(%) and B/D ratio. So these two variables were removed and multiple regression analysis was performed again. For this model a value of 0.765 for $R^2$ was obtained, indicating that 76.5 percent of the variation in the measure is explained by the linear regression model. Both the F-test and t-test were satisfactory, valid F test (Significance F < 0.05), and all of variables are significant, T test (P-value < 0.05). So the proposed model is:

$$y = 130.29 - 25.85 x_1 - 0.0115 x_2 - 0.57 x_3 - 0.27 x_4 - 3.847 x_5$$

where $y$ = LOG(NFC) *NFC = Number of failure cycles,
$x_1$ = LOG(MOR), *MOR = Modulus of Rupture
$x_2$ = Invert Slump
$x_3 =$ Air Content  
$x_4 =$ Unit Weight  
$x_5 =$ Stress Level

4 Conclusions

This study investigated the potential benefits of using fiber reinforced and low shrinkage concrete in pavements. The lab results indicated that toughness of concrete increased with increasing fiber content. The shrinkage testing indicated that there were small differences in unrestrained shrinkage for the control and the two low shrinkage mixtures. However, fiber reinforced concrete mixtures exhibited higher levels of shrinkage.

The fatigue analysis indicated that the addition of polypropylene fibers resulted in higher fatigue strengths. The fatigue strength of FRC increased with decreasing fiber content until 0.3 percent. Overall the best fatigue performance was obtained with the 0.1 fiber content mixture. The proposed fatigue models could be used in pavement design for conditions and materials similar to the considered in this study.

References

