Fatigue Behavior of Ultrahigh-Performance Fiber-reinforced Concrete as an Alternative for Flexible Pavement Rehabilitation[a]

Comportamiento a la fatiga de Concreto de Ultra alto desempeño reforzado con fibra como una alternativa en la rehabilitación de pavimentos flexibles

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Abstract

The fatigue behavior of ultrahigh-performance fiber-reinforced concrete for use as an overlay in the typical rehabilitation of a flexible pavement structure was analyzed in this study. Compression and four-point bending tests were carried out to characterize the concrete mechanical properties. Fatigue tests were performed using the four-point method, and test beams were evaluated without precracking. The specimens were subjected to constant-amplitude sinusoidal loading with a loading frequency of 10 Hz. The magnitude of each stress level was calculated as a percentage of the initial crack stress. The following results were obtained for the concrete: a compressive strength of 127.1 MPa, bending yield strength of 6.23 MPa, maximum bending stress of 9.89 MPa, Young's modulus of 38.1 GPa, and dynamic modulus of 28.6 GPa. The stress and strain at one million cycles were 6.0 MPa and 166 μm/m, respectively. The fatigue test results indicated superior properties of the ultrahigh-performance concrete to those of similar materials.

Keywords: UHPC, UHPFRC, fatigue, flexural, concrete, strain, stress, fiber, precracking.

Resumen

Esta investigación identificó el comportamiento a la fatiga de un concreto reforzado con fibras de ultra alto desempeño para su uso como sobrecarpeta en una rehabilitación típica de un pavimento flexible. Los procesos experimentales incluyeron una caracterización mecánica a compresión y flexión en cuatro puntos. La fatiga se realizó por el método de los cuatro puntos y las vigas de ensayo se evaluaron sin pre-fisuración. Las muestras se sometieron a una carga sinusoidal de amplitud constante con una frecuencia de aplicación de carga de 10 Hz. La magnitud de cada nivel de esfuerzo se calculó en porcentaje con respecto al valor del esfuerzo de fisuración inicial. Los resultados indicaron una resistencia a la compresión de 127,1 MPa, límite elástico por flexión de 6,23 MPa, esfuerzo máximo de flexión de 9,89 MPa, módulo de Young de 38,1 GPa, y módulo dinámico de 28,6 GPa. Esfuerzo y deformación a un millón de ciclos de 6,0 MPa y 166 μm/m respectivamente. Los resultados de fatiga indicaron un comportamiento superior para el concreto de ultra alto desempeño que el comportamiento de fatiga de otros materiales similares.

Palabras Clave: UHPC, UHPFRC, fatiga, flexión, concreto, deformación, esfuerzo, fibra, pre-fisura.

Introduction

As highways age and deteriorate, treatment is required to provide safe and serviceable facilities for the users. Treatment can range from simple maintenance to complete reconstruction, depending on the circumstances [1]. Highway engineers have used whitetopping as early as 1918 [2]. Whitetopping involves placing a thin concrete overlay directly over an existing distressed hot-mix asphalt (HMA) pavement to increase the structural capacity and therefore, the useful life, of the covered pavement structure [3][4]. Thin whitetopping refers to 102 to 152 mm (4 to 6 in.) overlay, and ultrathin whitetopping (UTW) consists of placing a 50 to 102 mm (2 to 4 in.) Portland cement concrete (PCC) overlay on an asphalt pavement [5]. The development of high-performance concrete (HPC) with a compressive strength between 50 and 120 MPa [6] has made it possible to create UTW [7][8].

Ultrahigh-performance concrete (UHPC) or ultrahigh-performance reinforced concrete (UHPFRC) are materials with a cement matrix, a characteristic compressive strength above 150 MPa (that can reach 250 MPa depending on the curing system [9]), high ductility, and excellent durability. According to the Federal Highway Administration [9], average compressive strengths of 150 MPa and above 5 MPa are expected for tensile strength pre- and postcracking, respectively. UHPFRC mixtures with strengths between 110 MPa and 230 MPa that are sensitive to curing have been reported [10][11]. These properties are obtained by optimizing the density packing and choosing a suitable cement, superplasticizer and mixing procedure [12][13]. In addition, several studies ([14][15][16][17]) have been performed to determine the static mechanical properties of UHPC, such as the compressive strength, modulus of rupture, elastic modulus, and tensile strength. In addition to exhibiting desirable mechanical and durability characteristics, this new generation of UHPFRC concretes also offer a rapid increase in strength and stiffness at early curing stages. However, the fatigue performance of these materials is an important parameter that requires further study for some applications.

UHPC is a new engineering solution for different applications, such as the construction and rehabilitation of bridges [18] [19], including pedestrian bridges [20] and railway bridges [21], and the construction of different types of structures [22]. High-performance reinforced concrete (HPFRC) and ultrahigh-performance concrete (UHPC) are frequently used in construction, can be subjected to fatigue loads and are expected to resist millions of cycles during their service life. Cyclic loads significantly affect the characteristics of materials and can cause fatigue failure [23]. It is necessary to evaluate the dynamic behavior or fatigue of the concrete material in some cases, for example, pavements.

As pavement structures are normally subjected to repetitive fatigue loads, static mechanical data are insufficient for predicting pavement performance [24], even for those pavements containing UHPC. To enable the application of UHPC as a pavement structure layer, it is necessary to study the fatigue life as a parameter to be included in the pavement design and to be controlled during pavement operation. The subject of this study is the application of ultrahigh-performance concrete (UHPC) to build an even ultrathin whitetopping (less than 50-mm thick) as an alternative to flexible pavement rehabilitation.

Materials and mix design

Concrete mixture

The materials used to produce UHPFRC in this study included Portland cement, calcium carbonate ($CaCO_3$), silica fume, natural river sand, a polycarboxylate-based high-range water-reducing superplasticizer (SP), steel fibers and water. Table 1 summarizes the mix proportions of the UHPC produced in this study.

Table 1. Mix proportions of UHPFRC

Materials		Weight Proportions Per Mass of Cementitious Materials [kg]	Total Mix Weight [%]
Cementitious Materials	Portland Cement (58.3%)	1	51.5
	Calcium Carbonate (25.0%)		
	Silica Fume (16.7%)		
	Water	0.20	10.3
Aggregates	Natural River Sand (Maximum Particle Size 600 μm)	0.59	30.8
Admixture	Polycarboxylate-based High-range Water-reducing Superplasticizer	0.02	0.9
Reinforcement	Steel Fiber - 13 mm	0.13	6.5

Source: Authors

The Portland cement used for UHPFRC production exhibited high resistance at an early curing stage (Portland cement type III [25]). Tables 2 and 3 show the mechanical, chemical and physical properties of the cement.

Table 2. Chemical composition of raw materials

Constituent		Cement Proportion [%]
Silicon Dioxide	SiO_2	20.9
Aluminum Oxide	Al_2O_3	4.8
Iron Oxide	Fe_2O_3	3.3
Calcium Oxide	CaO	63.6
Magnesium Oxide	MgO	0.9
Sulfur Trioxide	SO_3	2.3
Sodium Oxide	NaO_2	0.1
Potassium Oxide	K_2O	0.8
Chromium Oxide	Cr_2O_3	0.02
Manganese Oxide	MnO	0.04
Phosphorus Oxide	P_2O_5	0.27
Titanium Oxide	TiO_2	0.3
Loss On Ignition	(LOI)	3.5

Source: Authors

Table 3. Properties of Portland cement

Property	Value
Compressive Strength (ASTM C39 [26])	54.1 MPa
Density (ASTM C39 [26])	3100 kg/m^3
Initial Setting Time (ASTM C191 [27])	136 minutes
Final Setting Time (ASTM C191 [27])	195 minutes
Fineness (ASTM C204 [28])	480.8 m^2/kg

Source: Authors

Manufacture of test samples

The preparation process of UHPFRC was as follows. First, the water and superplasticizer were mixed for 1 minute. Second, the Portland cement, calcium carbonate, and silica fume were added to the mixture and mixed for 8 minutes or until a fluid mixture was obtained. Third, the sand was added in two stages until a homogeneous and fluid mixture was obtained. The maximum time to manufacture the UHPFRC was 20 ± 2 minutes.

Fresh concrete was poured into oiled molds to form cylinders, cubes, beams, or slabs, as stated in the respective test standard. The effect of the fiber orientation on the UHPFRC flexural strength [29] [30][31] is a source of concern in regard to performing a flexural fatigue test that is expected to represent natural pavement conditions. For this reason, the concrete was poured into a mold to form a slab and then cut into beams. The formwork of the specimens was removed at 24 hours, and the specimens were cured in air, without humidity or temperature control, over the prescribed testing period. Curing was performed without humidity or temperature-controlled conditions to simulate critical real pavement curing conditions. Table 4 shows the size of the specimens used in different tests.

Table 4. Sample shape and size for different tests

Test	Specimen Form	Sample	Size
Compressive Strength	Cube	8	50 x 50 mm
Flexural Strength	Beam	6	50 x 50 x 400 mm
Flexural Fatigue	Beam	16	50 x 50 x 400 mm

Source: Authors

The beam size was chosen considering the sand particle size and the predicted dimensions of the cross-section of the UHPFRC pavement slab [32]. The maximum load of the test machines used for testing was also considered in selecting a beam size.

Test Methods

Compressive strength test

The compressive strength of the specimens was measured using a computer-controlled universal testing machine. The test age was 28 days. The test was performed according to the Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [26].

Flexural strength test

A static monotonic four-point bending test was performed to determine the flexural strength of the specimens(ASTM C78 [33]) using a material testing system (MTS) (Figure 1). The test is carried out by applying a monotonic and continuously increasing load until concrete failure [34]. The first measured crack (σ_{fc}) strength was taken as the yield point of the material. Additionally, σ_{fc} was used as a reference point r for calculating the magnitude of different stress levels during the fatigue test. Figure 2 (a) is a schematic of the typical behavior of the material. σ_{max} is the maximum flexural stress.

Figure 1. Flexural Strength Test - Material Testing System

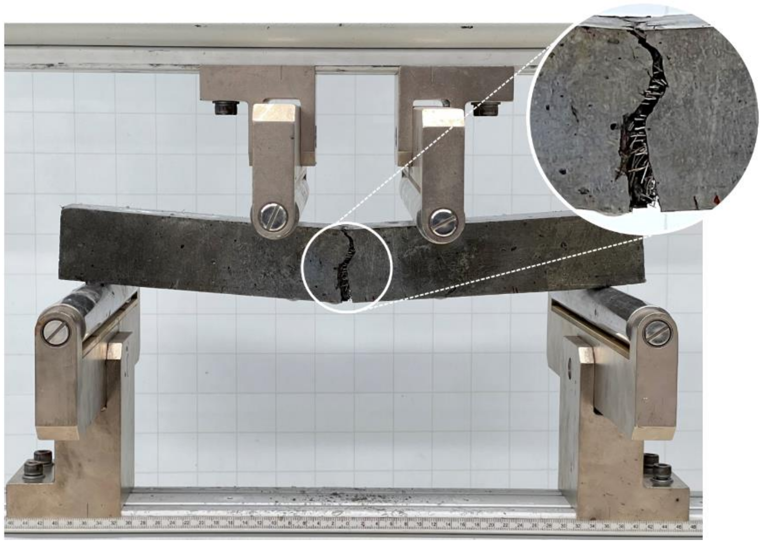

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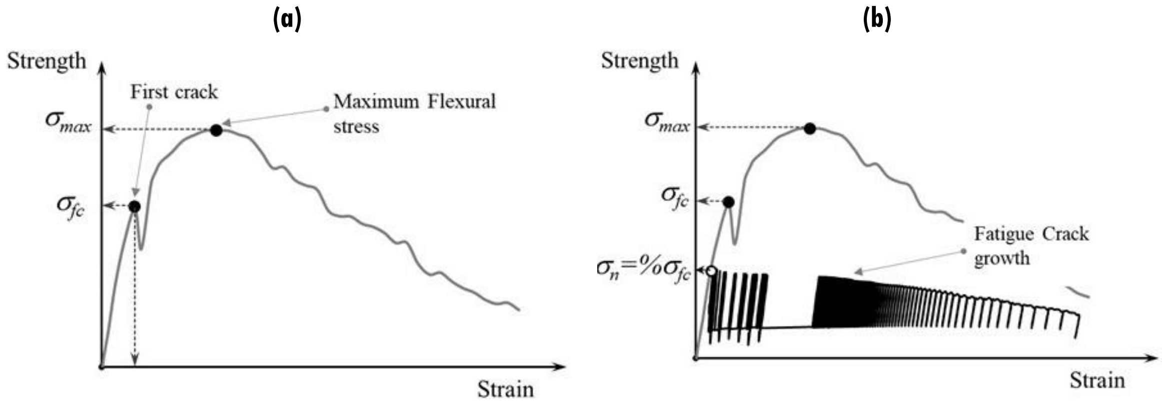
Figure 2. Schematic of flexural strength behavior *(a)*. Schematic of fatigue loading history *(b)*



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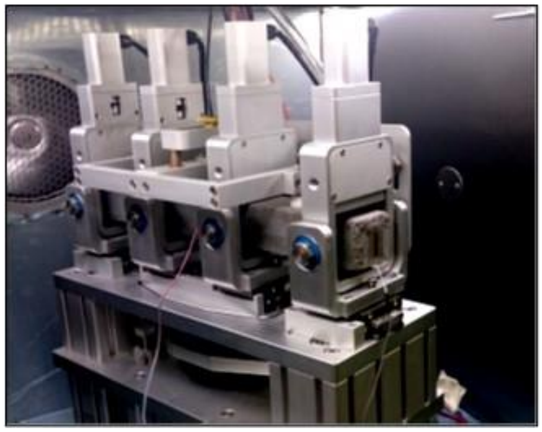
Flexural fatigue test

A fatigue test is performed by applying a dynamic load to a sample and monitoring the stress or strain in the sample [35] [36]. Monismith (1969) found a relationship between the layer thickness and loading mode of a sample [36]. For a pavement layer cast with a thickness below 50.8 mm (2 in), a fatigue test must be performed under controlled strain, given that the tensile strain is mainly controlled by the underlying layer stiffness [36].

A four-point bending beam machine was used to perform the flexural fatigue tests (Figure 3). The specimen was subjected to constant-amplitude sinusoidal loading with a loading frequency of 10 Hz. This frequency has been used in several studies on reinforced concrete [37] [38] [39] [40] [41]. Unlike in other studies [42] [43], the samples were not precracked to assess the material performance. The magnitude of each stress level *(σ_n)* was calculated as a percentage (98%, 97%, 96% and 95%) of the initial crack stress *(σ_{fc})*. Figure 2 (b) is a schematic of the fatigue test for one stress level *(σ_n =% σ_{fc})*.

Figure 3. Flexural Fatigue Test – Four-point Bending Beam Machine



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Test results and discussion

Compressive Strength

The test results indicated that the UHPFRC used in this study has a compressive strength of 127.1 MPa with a coefficient of variation of 4.9%.

The compressive strength results confirm that the concrete mix cured under the conditions mentioned above could be cast into a pavement slab and still achieve a compressive strength of over 100 MPa. Other authors have found a coefficient of variation of the compressive strength of UHPFRC of between 1 and 10% [31].

Flexural strength

Table 5 shows the flexural strengths of all the specimens on the 28th day of curing.

Table 5. Flexural Strength Test Results

Test	Mean	Coefficient of Variation
Maximum Flexural stress (σ_{max})	9,8 MPa	24,6 %
Initial Crack Stress (σ_{fc})	6,2 MPa	9,1 %
Initial Crack Strain (ε_{fc})	171,0 μm/m	1,0 %
Flexural Young's Modulus	38,128 GPa	12,9 %

Source: Authors

The results for the material characteristics indicate a high dispersion for the maximum flexural stress, which results from the highly divergent measurements across specimens past the yield point. However, the yield point exhibits low dispersion in terms of both the stress and strain values. In previous studies, these values have been established as typical for UHPFRC due to the material rheology, where the coefficient of variation was determined to be between 20 and 30% for the maximum flexural stress [29], between 12 and 28% for the yield stress [29] and between 7.4 and 14.7% for the flexural Young's modulus [31]. A reference value for the coefficient of variation was not found for the initial crack strain. Nevertheless, the coefficient of variation found in this study demonstrates that the initial crack strain could be used as a control parameter during pavement service. The magnitude of each stress level was calculated as a percentage of the initial crack stress.

Flexural Fatigue Test Results

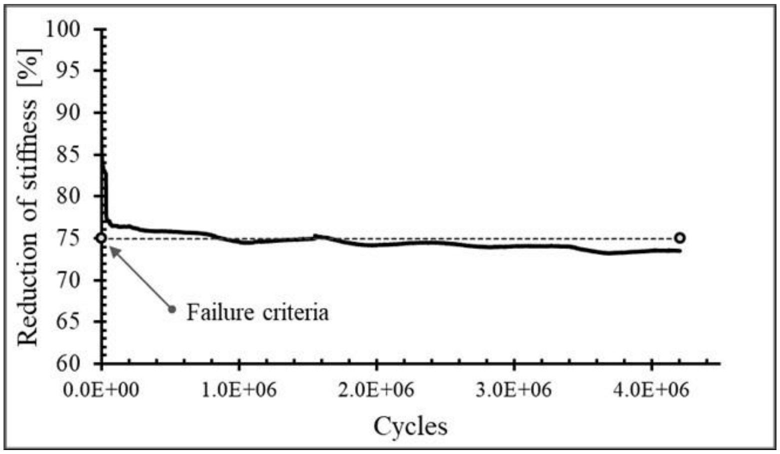
Behavior of steel-fiber-reinforced UHPFRC under cycling flexural loads

Figure 4 shows the stiffness reduction with respect to the cycle number. The stiffness reduction asymptotes at approximately 75% of the initial stiffness; thus, the failure criterion was defined in terms of the extent of the stiffness reduction.

Figure 4 shows that the steel-fiber-reinforced (UHPFRC) specimens typically fatigued at an early stage.

1. The initial damage stage: The material lost approximately 25% of its initial stiffness between 1 and $1x10^4$ cycles. Microcracks began to appear in the concrete, and the sample strength was transferred from the concrete matrix to the steel fibers, resulting in a rapid decrease in the stiffness.
2. The stable damage expansion stage: The rate of stiffness reduction stabilized at approximately 75% of the initial stiffness. As the strain was controlled during the test, the concrete matrix and steel fibers were able to resist the applied loads without an increase in the damage to the specimen.

Figure 4. Percentage of the initial stiffness vs. the number of cycles for a specimen in a fatigue test under a 97% controlled maximum strain



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Similar behavior was reported by Wang, Sigang, and Hongzhe in 2006 [38] for carbon-fiber-reinforced concrete under cyclic flexural loading.

Fatigue Equation

Several specimens were tested under different controlled strain levels to determine the fatigue behavior of the concrete. The plot of the strain vs. the number of cycles is known as the Wöhler curve, and a curve regression analysis yields the fatigue equation of the material [44]. This equation often takes the form of a double-logarithm. The typical fatigue law of hydraulic concrete materials is $\log(\sigma) = \log(a) + \log(\alpha)$., where σ is the tensional stress, N is the concrete fatigue life, and α and β are parameters related to the concrete fatigue performance [37].

The parameter α reflects the strain in the steel-fiber-reinforced UHPFRC at the yield point. The larger α is, the steeper the fatigue curve is, and the better the fatigue performance of the concrete is [37]. The parameter β reflects the change in the number of cycles that the material can achieve for a change in the controlled stress or strain value. The larger β is, the steeper the fatigue curve is, and the more sensitive the concrete fatigue is to changes in the stress or strain [37]. Figures 5 and 6 show the logarithmic regressed fatigue curve of steel-fiber-reinforced UHPFRC based on eleven strain control tests, which is similar to those reported in the literature [39] [45] [43]. Some data points may need to be rejected as outliers, as has been reported in another study [39].

Figure 5. UHPFRC Fatigue Curve and Equation, Stress vs. Number of Cycles.

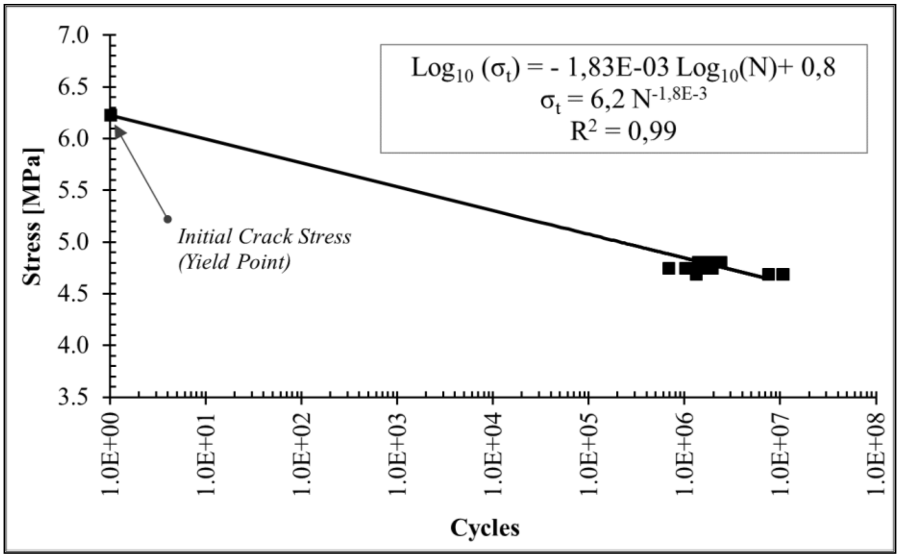

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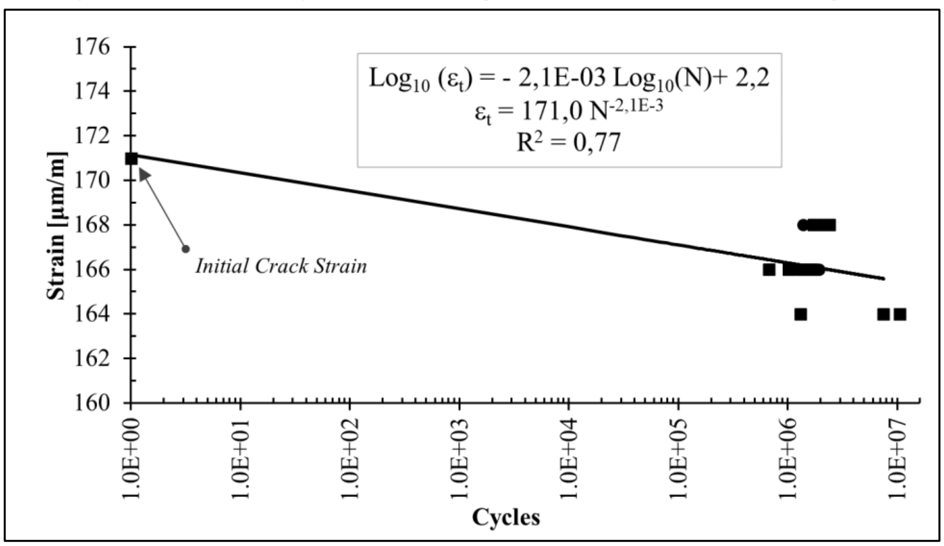
Figure 6. UHPFRC Fatigue Curve and Equation, Strain vs. Number of Cycles.



Source: Authors

Figures 5 and 6 show the fatigue equation with an α of 6.2 MPa (equivalent to 171 µm/m), where β is -1,8x10^{-3} and -2.1x10^{-3} when the fatigue equation is presented in terms of the stress and strain, respectively. The results show that at one million cycles, the admissible stress (σ_6) is 6.0 MPa, and the tensile strain (ε_6) is 166 µm/m.

The UHPFRC fatigue performance is compared against those of similar materials to identify improvement in the fatigue performance. Table 6 presents a comparison of the performances of UHPFRC and materials reported in other studies.

Table 6. Comparison of different concrete materials used to rehabilitate flexible asphalt pavement structures.

Material	β	σ_6 [MPa]
Ultrahigh-performance Fiber-reinforced concrete	-1.8×10^{-3}	6.0
Steel-fiber-reinforced Concrete [46]	-30.0×10^{-3}	5.6
Steel-fiber-reinforced Concrete [40]	-45.5×10^{-3}	5.6
Glass-fiber-reinforced Concrete [41]	-38.8×10^{-3}	0.7

Source: Authors

Conclusions

The results of flexural tests results performed in this study show that steel-fiber-reinforced UHPFRC is a strong material with a broad elastic region. There was low dispersion (below 1%) in the data for the initial crack strain, which could therefore be used as a control parameter. Hence, this material is adequate for use as a concrete layer over an existing pavement.

The steel-fiber-reinforced UHPFRC retains sufficient integrity beyond the initial crack stress (yield point) to operate as a pavement layer. The performance of this material in the plastic region, that is, postcracking, should be investigated in future studies.

The results of the fatigue tests performed in this study show that the stiffness of the steel-fiber-reinforced UHPFRC is reduced by 25% under a dynamic load because of microcracking in the concrete matrix and that the concrete-fiber interaction provides load resistance to realize higher strains than other kinds of hydraulic concrete. This property can enhance the performance of a rehabilitated pavement structure.

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