Fracture Mechanism of Fibre Reinforced Concrete Pavement Based on a RILEM Design Approach

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Abstract. Using fibre-reinforced concrete pavement (FRCP) offers excellent performance in terms of enhancing the concrete’s physical properties. The most popular fibres used in creating concrete for pavements are steel, polypropylene, and polyvinyl alcohol (PVA) fibres, though these come in a variety of geometries (lengths, shapes, sizes, and thickness). This paper utilises steel and PVA fibres at different low volume fractions to examine the improvement mechanism of FRC. The volume fractions of fibre (Vf) used were 0.04, 0.12, and 0.2 % and 0.3, 0.4, and 0.6% for PVA and steel hooked end fibres, respectively. There are many theoretical methods available for determining the effect of fibre inclusion on the load-carrying capacity of concrete pavements. One of these methods is analysing the stress-strain diagram (σ-ε method) according to RILEM TC-162-TDF. This paper used the (σ-ε) method to evaluate these types of fibre, showing that the stress-strain diagram, residual flexural tensile strength, and toughness are improved by adding both types of fibre. The improvement in fracture mechanisms enhances the ability of FRCP to bear stresses and moments, helping to avoid premature failure in the pavement. PVA FRC showed better performance than steel FRC in terms of supporting the external bending moment capacity, however, which reduces the thickness of the concrete required.

1. Introduction:
Low dosage of several fibre types in concrete have significant effect on the structural performance of such concrete [1]. Many studies have investigated the impact of different volume fractions of fibres on the compressive strength and modulus of elasticity in concrete [2, 3, 4], yet although many investigations have been carried out to evaluate the performance of fibre in terms of improving concrete pavement to prevent the formation of cracks and increase concrete toughness [5, 6, 7], these investigations have rarely examined the ability of fibres to assist the external bending moment capacity, reducing the thickness of the concrete pavement required. There are multiple different guidelines and design codes for steel fibre reinforced concrete, but there was no general analysis and design codes in the USA and Europe for other types of fibres. This obstacle prevents a widespread structural use of such fibres. RILEM, the International Union of Laboratories and Experts in Construction Materials, Systems, and Structures, has implemented many studies on FRC, and to assess fibre performance, RILEM TC 162-TDF is often utilized to evaluate the (σ-ε) curve, which in turn gives an indication of the energy absorption of concrete pavements. The energy absorption is represented by the area under the load-deflection (P - d) curve for up to length of span/150 mid-span deflection. This method determines (P - d) by performing a four-point bending beam test [8].
2. Approaches to Analyse Flexural Behaviour of FRC:

There are two approaches developed by RILEM TC 162-TDF: the first is the \((\sigma-\varepsilon)\) approach which determines the \((F-\delta)\) figure at the bottom of tested beams, and second is the \((\sigma-w)\) approach, which is based on mechanical fracture theory (fictitious crack model). The \((\sigma-w)\) approach depends on the stress-crack opening relationship \([\sigma(w)]\). Initially, work was carried out to analyse and calculate the ultimate limit state (ULS) based mainly on the first approach. The \((\sigma-\varepsilon)\) method was used by European code creators to design the specifications for steel fibre reinforced concrete, which is based on the same fundamental steps used in the design of normal reinforced concrete. Four tests are required to determine the parameters needed to evaluate the post-cracking behaviour, which are compressive strength, modulus of elasticity, compressive-strain in terms of peak strain value, and bending strength test. The \((\sigma-\varepsilon)\) compression diagram can be obtained from the compressive strength and modulus of elasticity testing of concrete cylinders based on ASTM C39 and ASTM C 469, respectively [9, 10]. The peak strain test uses one LVDT to obtain both the peak strain \(\varepsilon_0\) and ultimate strain at failure \(\varepsilon_u\). Figure 1 shows a complete stress-strain curve obtained from a concrete compressive test.

The \((\sigma-\varepsilon)\) tension diagram can be obtained from the bending strength test of a concrete beam according to ASTM C1609 [11]. For the standard test, the concrete specimen beam size is 152 x 152 x 610 mm. The beam is notched for 8.5 mm through the width of the beam in the middle of length using a saw, then the test is carried out using a four-point load at one-third of the support length (457 mm).

The \((F-\delta)\) diagram provides the residual flexural tensile strength by determining the limit of proportionality \(f_{ct,fl}\) and equivalent flexural tensile strength \(f_{eq,2}\) and \(f_{eq,3}\). The \(f_{ct,fl}\) is calculated based on the pre-peak load \(f_L\) the \((F-\delta)\) diagram. The \(f_{eq,2}\) and \(f_{eq,3}\) represent the force according to the area under the \((F-\delta)\) curve.

As shown in Figure 2, \(\delta_{F_L}\) is the deflection at pre-peak load \(f_L\), \(\delta_2\) is the deflection at 0.65 from clear height \(H_{sp}\), and \(\delta_3\) is the deflection at 0.9 from clear height \(H_{sp}\). The \(D_{BZ,2,11}^f, D_{BZ,2,11}^f, D_{BZ,3,11}^f,\) and \(D_{BZ,3,11}^f\) are the contribution of fibre to energy absorption capacity (lb.in). Assuming a linear stress distribution at midspan, as Figure 3 shows, the moment at midspan of a supported beam will be equal to:

\[
M = \frac{F \cdot L}{6} \tag{1}
\]
As presented in Equation 1, \( F \) is the load (lb), and \( L \) is the beam length (inch). The residual flexural tensile stress is thus computed as follows:

\[
f = \frac{M \cdot C}{I}
\]

where

\[
\frac{C}{I} = \frac{6}{b \cdot h^2} \Rightarrow f = \frac{F \cdot L}{b \cdot h^2}
\]

Therefore,

\[
f_{ct,f1} = \frac{F \cdot L}{b \cdot h^2}
\]

The \( f_{eq,2} \) and \( f_{eq,3} \) are calculated based on the linear elastic behaviour assumption, as shown in Figures 4a and 5a. However, in reality, the stress distribution is different, with the elastic stress being inequivalent to plastic stress. RILEM proposed an assumption that the tensile stress in FRC beams can be often determined at the beam’s cracked zone, as seen in Figures 4b and 5b.
Figure 4: Stress distribution depends on the length of crack (0.65 h).

Figure 5: Stress distribution depends on the length of crack (0.90 h).

From Figure 4, the bending moments in the compression and tension zones can be calculated using Equations (4) and (5), respectively:

\[
M_1 = \frac{b \cdot h_{sp}^2}{6} f_{eq.2} \\
M_2 = 0.65 \cdot h_{sp}^2 \cdot 0.56 \cdot b \cdot \sigma_2
\]

The \( \sigma_2 \) is thus obtained by substituting Equation (5) into Equation (4):

\[
\sigma_2 = 0.45 \cdot f_{eq.2}
\]

From Figure 5, the bending moments in the compression and the tension zones can be calculated using Equations (7) and (8), respectively:

\[
M_1 = \frac{b \cdot h_{sp}^2}{6} f_{eq.3} \\
M_2 = 0.9 \cdot h_{sp}^2 \cdot 0.51 \cdot b \cdot \sigma_3
\]
The $\sigma_3$ is thus obtained by substituting Equation (8) into Equation (7):

$$\sigma_3 = 0.37 \cdot f_{eq,3}$$

(9)

Once the $\sigma_2$ and $\sigma_3$ are calculated using Equations (6) and (9), respectively, the stress-strain diagram of the tension zone of the FRC concrete beam can be created. Figure 6 illustrates the complete stress-strain curve at the tension zone of the concrete beam.

**Figure 6**: stress-strain diagram in tension (Vandewalle, 2000).

3. Database of FRC

In this work, the data for seven different mixtures with 19 mm maximum size aggregate and a 0.45 water to cement ratio were used. Two types of fibres were utilised. The first was steel with hooked ends at volumetric fractions of 0.3, 0.4, and 0.6%. The properties of steel hooked end fibre are 7.8 specific gravity, 1,138 MPa tensile strength, 1.5 mm cut lengths, and 200 GPa flexural strength. The second fibre type was PVA in volumetric fractions of 0.04, 0.12, and 0.2. The properties of PVA fibre are 1.3 specific gravity, 1,655 MPa tensile strength, 0.25 mm cut lengths, and 38 GPa flexural strength. Figure 7 shows the steel and PVA fibres used in the experimental work. Three different laboratory tests were carried out: compressive strength testing, modulus of elasticity, and load-deflection based on flexural test.

**Figure 7**: Types of Fibre Used in Experimental Work
Table 1 outlines the mechanical properties of the of PVA400 and steel fibre reinforced concrete as compared to plain concrete.

| Mix. | Type and Volume Fraction of Fiber | Compressive Strength (MPa) | Modulus of Elasticity (GPa) |
|------|----------------------------------|---------------------------|-----------------------------|
| Control | -                               | 36.37                     | 32.82                       |
| PVA 400 | PVA 400 (0.04%) | 39.77                     | 30.23                       |
|        | PVA 400 (0.12%) | 40.23                     | 31.86                       |
|        | PVA 400 (0.2%) | 41.45                     | 32.34                       |
| Steel  | Steel (0.3%) | 44.53                     | 30.57                       |
|        | Steel (0.4%) | 44.74                     | 31.62                       |
|        | Steel (0.6%) | 51.44                     | 32.22                       |

The effect of type and volume fraction of fibre on the stress-strain curve of the concrete under compression are shown in Figures 8.

**Figure 8:** PVA-FRC and S-FRC Stress-Strain Curves in Compressive.

Figure 9 shows the load-deflection curves from flexural tests of plain concrete, PVA-FRC, and steel-FRC, which were used to determine the stress-strain diagram, residual flexural tensile strength, and toughness.

**Figure 9:** Flexural Load-Deflection Curve of PVA-FRC and S-FRC
4. Analysis of Results

All the beam series were designed according to RILEM TC-162-TDF [8], and these are evaluated in this section. From the data gathered during bending strength tests, the load-deflection curves at mid-span, and crack widths were determined for each beam. The diagrams show that the steel fibre was better than PVA fibre in terms of bearing tension stresses, as shown Figures 10 and 11.

![Stress-Strain Diagram for PVA 400 (Vf = 0.12%)](image1)

**Figure 10**: Stress-Strain Diagram for PVA 400

The behaviour of the PVA-FRC beam with a low volume fraction of 0.04% was similar to the behavior of the plain concrete beam, and no stress-strain diagram was identified for Vf = 0.04%.

Table 2 summarises the results calculated from the equations of residual flexural tensile strength and toughness for the concrete samples. The equivalent flexural tensile strength parameters, f(eq2), to represent the post-cracking energy absorption capacity, and the equivalent flexural tensile strength values are seen to be directly dependent on the energy dissipated up to a given deflection. Additionally, the concept of the residual flexural tensile strength (σr) was used to gather necessary information about the shape of the post-peak load-deflection relationship.
Figure 11: Stress-Strain Diagram for Steel Fibre
Table 2: Residual Flexural Tensile Strength and Toughness for Concrete.

| Type of Fiber | Vf (%) | F2 (MPa) | F3 (MPa) | Kh (mm) | f(eq,2) (MPa) | f(eq,3) (MPa) | σ2 (MPa) | σ3 (MPa) | f(fct,fl) (MPa) |
|---------------|--------|----------|----------|--------|--------------|--------------|----------|----------|----------------|
| PVA 400       | 0.04   | 22.67    | 21.30    | 24.51  | 2.12         | 1.99         | 0.99     | 0.76     | 4.31           |
|               | 0.12   | 18.23    | 15.10    | 24.51  | 1.70         | 1.41         | 0.79     | 0.54     | 4.09           |
|               | 0.2    | -        | -        | -      | -            | -            | -        | -        | 4.74           |
| Steel         | 0.3    | 30.49    | 34.48    | 24.51  | 2.84         | 3.22         | 1.33     | 1.23     | 3.95           |
|               | 0.4    | 42.15    | 57.74    | 24.51  | 3.93         | 5.39         | 1.83     | 2.07     | 4.89           |
|               | 0.6    | 45.22    | 44.90    | 24.51  | 4.22         | 4.19         | 1.97     | 1.61     | 5.79           |
| Control       | -      | -        | -        | -      | -            | -            | -        | -        | 3.68           |

According to RILEM TC 162-TDF [8], verification of the serviceability limit state is evaluated using f(eq2) and σ2 while the verifications of the ultimate limit state is evaluated using f(eq3) and σ3. The equivalent flexural tensile strength parameters [f(eq2) and f(eq3)] have similar values as the same behaviour of residual flexural tensile strength, (σ2 and σ3). In general, a small decrease of the f(eq2), f(eq3), σ2 and σ3 with the increase of volume fraction of PVA-FRC was observed, along with a small increase of the f(eq2), f(eq3), σ2 and σ3 with the increase of volume fraction in S-FRC.

Table 3 shows the compressive and tensile strength and Z distance for each FRC mix. The moments at the ultimate stage were calculated using the stress-strain distribution in compression and tension data. The tensile strength resultant and neutral axes were then calculated using an area balance according to the stress-strain distribution in compression and tension. The internal ultimate moment capacities for FRC were identified based on RILEM TC-162-TDF. The results showed the ultimate moment capacities increasing with the increase in volume fraction of fibre despite very low ultimate moment capacities.

Table 3: Compressive Strength and Tension Strength and Z distance.

| Type of Fiber | $F_{fc}$ (MPa) | $F_{fct}$ (MPa) | Z (mm) | Internal Ultimate Moment Capacities (kN.m/m) |
|---------------|----------------|-----------------|--------|-------------------------------------------|
| Control       | -              | -               | -      | -                                         |
| PVA 400 (0.04%) | -              | -               | -      | -                                         |
| PVA 400 (0.12%) | 35.99          | 1.77            | 29.51  | 7.5                                       |
| PVA 400 (0.2%)  | 36.67          | 2.25            | 33.93  | 11.0                                      |
| Steel (0.3%)   | 38.03          | 1.43            | 22.66  | 4.7                                       |
| Steel (0.4%)   | 38.18          | 2.13            | 25.86  | 7.9                                       |
| Steel (0.6%)   | 42.13          | 2.43            | 27.36  | 9.6                                       |

* when the crack length 90% length of $h_{sp}$ (clear height) = 144 mm, and b (beam width) = 152 mm.
* $x=10\% \times 144 =14.4$ mm
As shown in Table 3, the internal ultimate moment capacities of 0.12% volume fraction of PVA-FRC were the same as for 0.4% S-FRC, while PVA-FRC with 0.2% volume fraction produced higher values than S-FRC with 0.6% volume fraction. This indicates that the PVA-FRC showed better performance than S-FRC in terms of managing the external bending moment capacity, which reduces the thickness of the concrete required.

5. Conclusion:
- The equivalent flexural tensile strength parameters \( f(\text{eq}_2) \) and \( f(\text{eq}_3) \) have similar values as the equivalent residual flexural tensile strength, \( \sigma_2 \) and \( \sigma_3 \).
- \( f(\text{eq}_2) \), \( f(\text{eq}_3) \), \( \sigma_2 \), and \( \sigma_3 \) decreased slightly with an increase of volume fraction of PVA-FRC, while a small increase of the \( f(\text{eq}_2) \), \( f(\text{eq}_3) \), \( \sigma_2 \) and \( \sigma_3 \) occurred with the increase of volume fraction of S-FRC.
- The ultimate moment capacities increase with the increased volume fraction of fibre despite very low ultimate moment capacities.
- The internal ultimate moment capacities of 0.12% volume fraction PVA-FRC had the same value as 0.4% S-FRC. However, PVA-FRC with 0.2% volume fraction had a higher value than S-FRC with 0.6% volume fraction.
- PVA-FRC showed better performance than S-FRC in terms of accommodating external bending moment capacity, which reduces the thickness of the concrete required.

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