CHAPTER IV
CHARACTERIZATION OF MECHANICAL PROPERTIES OF RPC

Reactive Powder Concrete (RPC) represents a technological leap ahead for the construction industry. Among already built outstanding structures, RPC lies at the forefront in terms of innovation, aesthetics and structural efficiency. Beginning with Richard and Cherezy (1995), many researchers have investigated the various aspects of RPC. However, proper selection of materials, their proportioning and process of production, influence the rheological properties and mechanical performances of Reactive Powder Concrete. For the design of RPC structural components, one of the important requirements is the stress-strain behavioral model. Not much published information is available about the stress-strain characteristics of RPC under compression and tension. The study focuses on the stress-strain behavior of RPC under uniaxial compression, Flexure, Direct Tension and Shear. The effect of fibre volume fraction and fibre length on the on the mechanical properties of RPC are reported.

4.1 STUDY OF COMPRESSIVE STRENGTH OF RPC

4.1.1 Stress-strain Behaviour of UHPFRC

Ultra-high performance fibre-reinforced concrete (UHPFRC) is a new class of concrete that has been developed in recent years. When compared with high performance concrete (HPC), UHPFRC exhibits
superior properties in terms of compressive behavior, tensile behavior, and durability.

4.1.2 Need for the Present Study

With growing populations in developing areas of the world, such as India, and with the decay of existing infrastructure in developed nations, such as the United States (US), the need for new materials with improved properties, which can provide higher performance, is as imperative now as ever. Advanced cementitious composites, which include fibres and particulate matter along with advanced chemical admixtures and complex binary, tertiary and even quaternary cement blends represent a growing proportion of the concrete being used and possibly the future norm.

i. Very few investigations reported on stress-strain behaviour of UHPC, Modelling has not been done,

ii. Effect of different parameters on stress-strain characteristics have not been investigated in detail and toughness index in compression has not reported.

4.1.3 Testing Program

The RPC cylinders of 100mm diameter and 200mm height were cast. This experiment were carried out, to observe the improvement in compressive behavior of the RPC on addition of different volumes of 6mm and 13mm fibres.
Figs-4.1 & 4.2 Experimental set up for cylinders under uniaxial compression

The specimen for compression tests consisted of 100mm diameter by 200mm long cylinders. Both the end of the specimen were carefully leveled and coated with sulphur to get plain and parallel surfaces. The experiment is carried out in a servo controlled compression testing machine as per ASTM C 469 procedure. All the tests were conducted after 28 days of respective curing periods. The tests were controlled with 2 LVDTs with 100 gauge length attached around the specimens at 180° spacing although it is well known that axial displacement is not the best control mode. Fig. 4.1 and Fig.4.2, show the experimental set up and instrumentation for measuring the deformation of specimen respectively. A typical stress-strain curve for one specimen for each volume of fibre is shown in Fig. 4.3 to 4.6. Stress-Strain curve varied linearly upto an elastic limit very close to peak load. It may be observed that the fibre reinforced RPC showed a modest increase in peak strengths with the increase in volume fraction of fibres and the difference in behavior was found in the post peak range. The addition of fibres caused a considerable contribution to ductility. In these cases,
the specimens failed in stable manner and the post peak softening branch were captured.

4.1.4 Discussions on Results

The important stress-strain parameters viz., the peak stress, the corresponding strain, the elastic modulus, the ultimate strain and the toughness indices by different mixes are shown in Table 4.1. As seen from the Table 4.1, the RPC mixes showed 112.6 to 246.8% higher compressive strength compared to normal concrete. The compressive strength generally increased with increase in fibre content in case of RPC mixes with 6mm fibres and 13 mm fibres. The highest compressive strength of 171.3 MPa was recorded for 2% 13 mm fibres. However, when fibre combinations of 6mm and 13 mm fibre were used, there was a reduction in compressive strength compared to highest compressive strength obtained for single size fibres. This could be attributed to the reduced workability and lower compaction density achieved as indicated by the density ratios show in Table 4.1. Therefore 3% of 6mm and 2% of 13 mm seem to be the optimum fibre contents as observed from the results obtained in the present study.
Table 4.1 Comparison of compressive strengths for various dosages of RPC

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Mix Type</th>
<th>Fibre content</th>
<th>Density Ratio</th>
<th>Stress at peak load (MPa)</th>
<th>Elastic Modulus GPa</th>
<th>Compression toughness Index</th>
<th>Strain at peak load X 10^6</th>
<th>Ultimate Strain x 10^6</th>
<th>Strain Ratio, ( \varepsilon_u / \varepsilon_p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RPC</td>
<td>0</td>
<td>1</td>
<td>105.0</td>
<td>34.5</td>
<td>0.56</td>
<td>0.56</td>
<td>2.64</td>
<td>3437</td>
</tr>
<tr>
<td>2</td>
<td>RPC</td>
<td>1% 6mm</td>
<td>0.97</td>
<td>122.7</td>
<td>39.0</td>
<td>0.62</td>
<td>0.60</td>
<td>2.51</td>
<td>3820</td>
</tr>
<tr>
<td>3</td>
<td>RPC</td>
<td>2% 6mm</td>
<td>0.94</td>
<td>145.8</td>
<td>42.0</td>
<td>0.68</td>
<td>0.64</td>
<td>3.47</td>
<td>4442</td>
</tr>
<tr>
<td>4</td>
<td>RPC</td>
<td>3% 6mm</td>
<td>0.89</td>
<td>161.8</td>
<td>44.0</td>
<td>0.66</td>
<td>0.59</td>
<td>3.95</td>
<td>4851</td>
</tr>
<tr>
<td>5</td>
<td>RPC</td>
<td>1% 13mm</td>
<td>0.94</td>
<td>136.9</td>
<td>41.0</td>
<td>0.67</td>
<td>0.66</td>
<td>3.29</td>
<td>4252</td>
</tr>
<tr>
<td>6</td>
<td>RPC</td>
<td>2% 13mm</td>
<td>0.91</td>
<td>171.3</td>
<td>44.8</td>
<td>0.66</td>
<td>0.62</td>
<td>3.63</td>
<td>4501</td>
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<tr>
<td>7</td>
<td>RPC</td>
<td>2%6mm+1%13mm</td>
<td>0.89</td>
<td>156.1</td>
<td>38.0</td>
<td>0.65</td>
<td>0.60</td>
<td>2.78</td>
<td>4751</td>
</tr>
<tr>
<td>8</td>
<td>RPC</td>
<td>2% 13mm+1%6mm</td>
<td>0.86</td>
<td>156.3</td>
<td>42.0</td>
<td>0.64</td>
<td>0.64</td>
<td>4.65</td>
<td>4900</td>
</tr>
</tbody>
</table>
Fig. 4.3 Comparison of Stress-strain Plots of RPC (l=6mm) with CC and HPC

Fig. 4.4 Comparison of Stress-strain Plots of RPC (l=13mm)
The elastic modulus of RPC mixes is found to be 44.4% to 87.4% higher than that of control concrete with the RPC mix with 2%-13mm fibre recording the highest elastic modulus of 44.8 GPa. The variation of
elastic modulus is found to follow a cube root of compressive strength as recommended by Eurocode 2 rather than a square root law as recommended by most of the codes of practice(Fig. 4.7). The ratio of ultimate to peak strain is the highest for fibre combination of 2% 13 mm and 1% 6mm(4.65) followed by 2% 13 mm(3.81) mix and 3% 6mm (3.73) mixes.

![Fig. 4.7 Variation of Elastic Modulus](image)

Toughness is a measure of the energy absorption capacity of the material and is used to characterize the materials ability to resist fracture. The toughness in compression is computed as the area under the stress-strain curve. Many nondimensional toughness indices have been proposed by the reaserachers for fibre reinforced concrete. Ezeldin and Balaguru [1999] defined the toughness index as the ratio of the area up to a strain of 0.15 to the area of a perfectly plastic material (expressed in MPa. mm/mm) with an yield strength equal to the peak strength and plastic strain of 0.15 (i.e., $\sigma_{cu} \times 0.15$). Taerwe and Gysel [1996] considered a maximum strain of 0.006, while Shreekala
et al [2006] used a value of 0.0075, as recommended by Japanese concrete Institute. In the present study, definition of Ezeldin and Balaguru [1999] has been used considering two strain limits 0.0075 and the ultimate strain. Ezeldin and Balaguru reported toughness index ranging from 0.48 for plain concrete to 0.76 for fibre concrete. However, as seen from Table 4.1, the values of toughness indices of RPC mixes as computed by this definition range from 0.561 to 0.675 and are of the same order as that of control concrete and HPC (0.58 to 0.66) and do not seem to show any significant variation with increase in fibre content and aspect ratio. A modified toughness index (MTI) was defined as the ratio of the area of stress-strain curve to pre-peak area of the curve. As seen from Table 4.1, the value of MTI ranges from 2.64 to 4.65 for RPC mixes and appears to be a better measure of the reinforcing action of fibres and their crack bridging action.

The ultimate strain values show the dominant effect of reinforcement effect and the length of fibre and it is interesting to note that 13 mm fibres enable higher ultimate strain to be reached as the 6mm fibres have a lower aspect ratio and may fail by fibre pull out rather than fibre fracture. The ratio of ultimate to peak strain is the highest for fibre combination of 2% 13 mm and 1% 6mm(4.65) followed by 2% 13 mm(3.83) mix and 3% 6mm (3.71) mixes.

The stress-strain characteristics depicted in Figs. 4.3-4.6 show that RPC mixes have a nearly linear ascending portion and strain at peak stress increases with increase in strength and reinforcement index. The post peak curve is strongly dependent on the fibre type and fibre
content and it is almost as steep as ascending curve for lower fibre contents and may be more gradually sloping for the higher fibre contents. The pattern of the curves is similar to that obtained by Jungwirth [2002]44, Bonneau et al., [1997]61 and Voo et al [2003]83.

Failure Pattern of typical plain and fibre reinforced RPC specimens is shown in Fig. 4.8 & Fig. 4.9. As can be seen, the typical failure is by crushing and spalling of concrete for plain concrete, formation of vertical cracks for lower percentage small fibre reinforcement and diagonal cracks for higher percentages of fibre reinforcement. It may be noted here that Jungwirth [2002]44 observed that the failure pattern was characterized by a typical diagonal crack. From Fig.4.9, it is observed that failure of specimens with higher fibre volume fractions is associated with multiple cracking and while more localized failure is evident in case of lower fibre volume fractions. The multiple cracking leads to higher failure strain and the redistribution of stresses leads to higher residual strength.

(a) Failed Fibre RPC   (b) Fibred RPC just Before Failure   (c)Plain RPC

Fig. 4.8(a-c) Typical Failure Pattern
(Fibre effect on Compression Failure)
Fig. 4.9 Failure Pattern of Specimens With Various Fibre Contents In Compression
4.1.5 CONSTITUTIVE MODELING FOR COMPRESSION SPECIMENS

4.1.6 Need for the Study

Reactive Powder Concrete (RPC) represents a technological leap ahead for the construction industry. Among already built outstanding structures, RPC structures lie at the forefront in terms of innovation, aesthetics and structural efficiency. Beginning with Richard and Cherezy (1995), many researchers have investigated the various aspects of UHPC. However, proper selection of materials, their proportioning and process of production influence the rheological properties and mechanical performances of UHPC. For the design of RPC structural components, one of the important requirements is the stress-strain behavioural model. Not much published information is available about the stress-strain characteristics of RPC. The chapter focuses on the stress-strain behaviour of RPC under uniaxial compression, tension, and its modelling. The effect of fibre volume fraction and fibre length on the stress-strain parameters is reported.

4.1.7 Constitutive Modelling for compression characteristics of RPC

The most common parameters with physical significance used to define the stress-strain relationship of steel fibre concrete include $\sigma_{cu}$ = the maximum stress of the fibre concrete, usually considered as the material strength; $\varepsilon_{cp}$ = corresponding strain to the maximum stress or the secant modulus $E_s$, initial tangent modulus $E_0$ and failure strain $\varepsilon_{cu}$; and $RI$ the reinforcing index by volume. Some of the important stress-strain models developed for concrete under uniaxial compression
was used for modelling the stress-strain data obtained in the present study. While Voo et al., [2003]\textsuperscript{83} used Thornfeldt model [1987]\textsuperscript{79} to model the stress-strain behavior RPC which is similar to that proposed by Collins [1993]\textsuperscript{13} and Carriera and Chu [1986]\textsuperscript{11} except for the expressions for the parameters n and k. While Thornfeldt et al [1987]\textsuperscript{79} expressed n and k as function of only peak compressive stress, Voo et al., [2003]\textsuperscript{83} expressed n as a function of initial tangent and secant modulus at the peak stress and used a constant of the various models. It is observed value of k=1 for both pre-peak and post peak portions. 

**Fig. 4.10** shows a comparison that the Collins et al., [1993]\textsuperscript{13} and Voo et al., [2003]\textsuperscript{83} model are very near to the experimental curve while they are rather inadequate in the post peak portion. The Desay et al., [1964]\textsuperscript{23}, model exhibits very mild post peak behavior and steeper pre-peak curve than the actual experimental curve. The post peak behavior was improved by modifying the parameter k to reduce the steepness of the post peak portion of the Voo's model\textsuperscript{83}. As seen in the Fig. 4.10, the modified Voo [2003]\textsuperscript{83} models as used in the present study gives the best agreement with the experimental data. This is confirmed from the comparison of presented in **Fig. 4.11.** Normalized Stress for various dosages of fibre is given in the **Fig. 4.12.** In general the coefficient of determination (R\textsuperscript{2}) ranged from 0.95 to 0.98 for the various mixes investigated indicating a satisfactory agreement. The following expressions were found to be appropriate for the parameters n and k(Equations 1 & 2 ).
\[
f_c/f_{cp} = \eta/(n-1+n^{nk}) \quad (1)
\]
\[
n = E_0/ (E_0-E_{SP}) \quad (2)
\]
\[
k = 0.75-0.075*RI \quad (3)
\]
where, \( E_0 \) = Initial tangent modulus,
\( E_{SP} \) = Secant modulus at the peak stress,
\( RI = V_f[l/f_d] \)
\( f_c, \dot{\varepsilon}_c \) = compressive stress and strain
\( f_{cp}, \dot{\varepsilon}_{cp} \) = compressive stress and strain at peak stress
\( \eta = \dot{\varepsilon}_c/\dot{\varepsilon}_{cp} \) = Strain ratio

Since the factor \( K \) regulates the post peak slope, it should be
appropriate that it should depend on the fibre content and aspect ratio.
Similarly the following formulae were derived from the experimental
data for the peak stress, elastic modulus and the ultimate strain as a
function of the reinforcement index and density ratio for the RPC mixes
(Equations 4 - 7).

\[
X = DR \times (RI)^{1.25} \quad (4)
\]
Peak stress, \( \sigma_{cu} = 105 + 1.0294X^3 - 15.595X^2 + 65.817X \quad (5)\]
Where, \( DR = \text{Density Ratio} = \text{Ratio of wet density of fibred RPC to that of plain RPC} \)
Initial tangent modulus,
\[
E = 34.74 + 8.2681X - 2.0018X^2 + 0.1388X^3 \quad (6)
\]
Failure strain,
\[
\varepsilon_{cu} = 7135.4 + 11567X - 3349.3X^2 + 261.47X^3 \quad (7)
\]
Secant modulus,
\[
E_{s} = 29.784 + 6.441X - 1.5722X^2 + 0.1022X^3 \quad (8)
\]
Softening Factor,

\[ K = 0.989 - 0.7393X + 0.5157X^2 - 0.105X^3 + 0.0064X^4 \]  \hspace{1cm} (9)

Fig. 4.10 Comparison of Different stress-strain Models for RPC

Fig. 4.11 Comparison of the Modified Voo Model and Experimental Stress –strain Curves
4.2 STUDY OF TENSILE PROPERTIES OF RPC

Tension tests were carried out to study the tensile characteristics of rpc. The tests were carried on the specimens (dog-bone shaped) with various dosages of fibre. The following paragraphs discuss the test procedure and the test results.

4.2.1 Objective

The main objective of this study is to investigate the stress-elongation of selected RPC using double-notched tensile specimens, and evaluate the influence of two variables, the length and quantity (Volume fraction) of fibres. Two different lengths of fibres(6mm,13mm) with seven different volume fractions (i.e.,1%-6mm,2%-6mm,3%-6mm,1%-13mm,2%-13mm,1%6mm+1%13mm, 1%6mm+2%13mm) are used. Key comparisons between different fibres are pointed out and conclusions drawn.

4.2.2 Research Significance

All cement-based composites reinforced with discontinuous fibres can be conveniently classified according to their tensile response,
namely either strain-softening or strain-hardening composites. RPC can fall into any of these categories depending on the fibre volume fraction, aspect ratio and fibre orientation and distribution. The post-cracking performance of reactive powder concrete in tension depends primarily on the characterization of the crack, which is a direct function of fibre and matrix characteristics, the bond between them, and the fibre content or volume fraction. While considerable studies have been reported on uniaxial compression and flexural behavior of RPC, only limited studies are available in respect of direct tension. The Structural engineering Research Centre has developed an RPC formulation. While the behavior of this material under compression has already been well investigated and reported [Graybeal 2006, Acker, 2004, Voo et al, 2003], the behavior in tension is of considerable interest for design purposed. It is believed that a displacement-controlled test can provide vital information on the tensile stress-strain response of the RPC mix. In addition, the effect of fibre combinations on the behavior, especially the strain hardening in tension, needs to be investigated.

4.2.3 Test Program

The most commonly used specimen geometrics for testing of UHPC (Ultra High Performance Concrete) behavior under tension were so-called dumb-bell prisms. To overcome the problems associated with specimen grips, end tapered specimen were tested in tension. The test was performed as a tension test on a clamped specimen. The specimen was fixed at both the ends in order to avoid eccentricity and rotation (Fig.4.13).
In the present test series the behavior was observed in the test as described in Jungwith and Muttoni (2004), and it is directly depends on the mechanical properties of the materials. Relevant changes in the structural behavior might result from using a different type and quantity of steel fibres.

![Tension test set up](image)

**Fig. 4.13 Tension test set up**

### 4.2.4 Testing Methodology

The test was performed as a direct tension test on a clamped specimen using a special loading jig. The specimens were fixed on both the ends. The wedges held in position by friction in order to avoid eccentricity and rotation (Fig.4.13). The test was conducted with a constant speed. To prevent the failure of the specimen under high stress concentration induced in the grips, the end portions were locally strengthened by carbon fibre reinforced polymer sheet bonded to the end surfaces using epoxy glue. The deformation was measured by 2-LVDTs (linear variable differential transducers) on either side. All tests were carried out using an MTS hydraulic testing machine, under displacement control. A data acquisition system was used to record the
force readings from the load cell of the testing machine as well as the
displacement from the two LVDTs. Complete stress-strain deformation
curves under uniaxial tension were obtained using a closed-loop servo-
hydraulic testing system.

4.2.5 Results and Discussions

The tensile properties of the different mixes viz., the tensile strength
at first visible crack and corresponding strain and peak stress and
corresponding strain and the failure stress and strain are indicated in
Table 4.2. Figs. 4.14 to 4.16 show the effect of different fibre types
and volume fractions on the stress-strain behavior. All the specimens
showed initially a linear elastic behavior as reported by Jungwirth and
Muttoni [2004] with a Young’s modulus of about 42 GPa. At about
70-90% stress level depending on the type and volume fraction of fibre,
the first visual crack appeared. This led to brittle failure for plain RPC,
but for fibreed RPC the stress increases up to 10-30% depending on the
fibre type and volume fraction, which is a feature of quasi-strain
hardening. Following cracking, a distinct change in slope of the tensile
stress-strain plot occurs but this effect is attributed to the high fibre
ratio i.e., the fibres crossing the crack have in total a higher strength
than the cement matrix. However, for low fibre volume fractions, quasi
strain hardening is rather negligible. The quasi strain hardening
behavior is similar to the Traditional reinforced concrete, characterized
by an increase of the capacity after cracking. During this stage multiple
cracks are created.
Table 4.2 Tensile Properties of Various RPC Specimens

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Sp. Id</th>
<th>Stress at First Crack (MPa)</th>
<th>Strain at First Crack (μm/mm)</th>
<th>Peak Tensile Stress (MPa)</th>
<th>Tensile strain at Peak Stress (μm/m m)</th>
<th>Stress at Failure (MPa)</th>
<th>Strain at Failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RPC0% fibre</td>
<td>3.98</td>
<td>215</td>
<td>4.18</td>
<td>250</td>
<td>4.18</td>
<td>0.0002</td>
</tr>
<tr>
<td>2</td>
<td>1%6mm</td>
<td>5.19</td>
<td>400</td>
<td>7.12</td>
<td>1100</td>
<td>3.45</td>
<td>8.1</td>
</tr>
<tr>
<td>3</td>
<td>1%13mm</td>
<td>5.85</td>
<td>700</td>
<td>7.15</td>
<td>1300</td>
<td>3.55</td>
<td>9.2</td>
</tr>
<tr>
<td>4</td>
<td>2% 6mm</td>
<td>6.53</td>
<td>700</td>
<td>8.09</td>
<td>2600</td>
<td>3.98</td>
<td>13.0</td>
</tr>
<tr>
<td>5</td>
<td>2%13mm</td>
<td>6.83</td>
<td>800</td>
<td>9.72</td>
<td>5900</td>
<td>4.55</td>
<td>12.0</td>
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<td>6</td>
<td>1%13mm+1%6mm</td>
<td>6.70</td>
<td>750</td>
<td>9.78</td>
<td>4900</td>
<td>4.62</td>
<td>10.0</td>
</tr>
<tr>
<td>7</td>
<td>3% 6mm</td>
<td>7.00</td>
<td>1200</td>
<td>9.85</td>
<td>4900</td>
<td>3.95</td>
<td>14.0</td>
</tr>
<tr>
<td>8</td>
<td>2%13mm+1%6mm</td>
<td>10.07</td>
<td>1300</td>
<td>12.44</td>
<td>13400</td>
<td>6.16</td>
<td>11.0</td>
</tr>
</tbody>
</table>

This multi cracking effect is regularly distributed over the whole length of the specimen and it can be assumed as smeared. The very small crack opening (micro-cracks) is just large enough to activate the fibres allowing the transfer of the stresses from the matrix. At a strain of about 1500-3000 microstrains, the bond strength of the fibres crossing the crack is reached in one of the cracks. The deformation localizes in this crack, which opens to become a macro-crack and propagates across the entire width. At this stage, the fibres are progressively pulled out and strain softening sets in (Fig.4.14 to 4.16). Finally, failure occurs when all the fibres across the major crack are fractured or pulled out so that no stress transfer could take place across the crack (Fig. 4.16).
Fig. 4.14 Tensile Stress-strain Curve for RPC with 6mm Fibres
Fig. 4.15 Tensile Stress-strain Curve for RPC with 13mm Fibres

Fig. 4.16 Tensile Stress-strain Curve for RPC with Fibre Combination
4.2.5.1 Effect of Fibres on Stress at First Crack

All the fibre reinforced specimens show initially a linear elastic behavior. At this stage, the fibres are supposed to have no influence and the behavior is taken to be governed by the cementitious matrix alone [Jungwirth and Muttoni, 2004]. However, as seen in Table 4.2, fibres have a significant influence on the tensile stress at first visible crack, which ranges from 5.19 to 10.07 MPa. For the specimens without fibre this leads to brittle failure. Whereas for low fibre volume fractions i.e., 1%-6mm and 1% 13 mm, there is a marginal increase of tensile strain by 600-700 microstrains accompanied by a corresponding stress increase. After first crack, strain softening sets in indicating that the stress carried by the fibres is less than the matrix strength after the first crack., the tensile strain of the RPC with high fibre content increases from However 1900 to as high as 12100 microstrains depending on the type and volume fraction of fibres indicating
considerable energy absorption. The effect is particularly evident in case of fibre combination especially in the presence of long fibres (13 mm). The large energy absorption occurs when large number of fibres exists across a crack so that the fibres crossing the crack have in total a higher strength than the cement matrix. The behavior is similar to the traditional reinforced concrete, characterized by an increase of the capacity after cracking. During this stage multiple cracks are induced.

**4.2.5.2 Effect of Fibre on Peak Stress**

The peak tensile strength ranges from 4.18 MPa (Plain RPC) to 12.44 MPa. (RPC with fibre) clearly elucidating the effect of fibre volume fraction on the tensile strength (**Table 4.3**). Even more dramatic than the stress level is the strain at peak load which ranges from 250 to 13400 micro strains, which demonstrates the tremendous advantage offered by fibre incorporation. Graybeal [2006]⁹, Jungwirth and Muttoni [2004]⁴⁴, Voo [2004]⁸³ have reported tensile strength from 6 to 11 MPa. Tensile strengths of about 14 MPa could be reached, with utilization of 4 vol.-% of short steel fibres [Behloul, 2004]⁸. Values of the tensile strength (about 12 MPa) were obtained by Markovic [2006]⁴⁰ for 1.5 % volume of both short and long fibres, and 2.0 % volume of only short fibres. For the same fibre volume content, long fibres resulted in a slightly higher tensile strength could be achieved. Increase of the fibre volume quantity leads to further improvement of the tensile behavior.

In the present study, there is no significant difference in the stress at first crack and peak stress between short and long fibres for the same
volume fraction and in fact 13 mm fibres showed marginally higher tensile strength (Table 4.3).

4.2.5.3. Effect of Fibre on the Residual Strength

The residual strength in the post peak domain is another measure of crack bridging and stress transfer mechanism of the fibres (Table 4.3). The residual strength of different RPC mixes at Residual strength is high for 2% 13mm fibres and fibre combination with 2% 13mm fibres than for the other dosages of fibre. It is observed that the residual strength ranges from 41% to 68% at a strain of 7500 μm/m and from 43 to 51.5 at a strain of 12% μm/m. Only specimens with greater than 2% volume fraction sustain up to 12%. It may be noted here that Jungwirth and Muttoni [2004] reported ultimate strain up to 10%. The results show that 2% 13mm fibres are ideal for direct tensile resistance for RPC mix as these fibres have an aspect ratio 80 and therefore perform well in the strain-softening portion.

Table 4.3 Residual Tensile Strengths of RPC under Direct Tension

<table>
<thead>
<tr>
<th>Specimen id</th>
<th>Peak Stress, MPa</th>
<th>Residual strength at the strain (μm/m) of</th>
<th>7500</th>
<th>10000</th>
<th>12000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MPa</td>
<td>% of Peak stress</td>
<td>MPa</td>
<td>% of Peak stress</td>
</tr>
<tr>
<td>1</td>
<td>1%6mm</td>
<td>7.12</td>
<td>2.93</td>
<td>41.2</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1%13mm</td>
<td>7.15</td>
<td>3.99</td>
<td>55.8</td>
<td>3.54</td>
</tr>
<tr>
<td>3</td>
<td>2% 6mm</td>
<td>8.09</td>
<td>5.5</td>
<td>68.0</td>
<td>4.60</td>
</tr>
<tr>
<td>4</td>
<td>2%13mm</td>
<td>9.72</td>
<td>6.09</td>
<td>62.7</td>
<td>5.25</td>
</tr>
<tr>
<td>5</td>
<td>1%13mm+1%6mm</td>
<td>9.78</td>
<td>6.06</td>
<td>62.0</td>
<td>4.83</td>
</tr>
<tr>
<td>6</td>
<td>3% 6mm</td>
<td>9.85</td>
<td>5.17</td>
<td>52.5</td>
<td>4.72</td>
</tr>
<tr>
<td>7</td>
<td>2%13mm+1%6mm</td>
<td>12.44</td>
<td>7.62</td>
<td>61.3</td>
<td>6.73</td>
</tr>
</tbody>
</table>
4.2.6 Constitutive modelling of concrete in tension

4.2.6.1 Modelling by EMIS(Enhanced Multilinear Isotropic Softning) Model

Several stress-strain models have been proposed to represent the behaviour of RPC under tension. Xiao and Chin [2004] presented an exponential type EMIS(Enhanced Multilinear Isotropic Softning) Model for nonlinear finite element analysis of conventional and fibre reinforced cementitious composites using ANSYS software to eliminate the problems associated with the convergence and instability in the post-cracking phase. The equations have been modified using suitable coordinates to suit the tension softening characteristics of fibrous concrete under uniaxial tension. The experimental results are analysed and correlated with the Xiao and Chin model and VEM model. The Xiao and Chin model is described by the Voce’s material constants as specified by the equation. The ascending and descending branches of stress-strain curves under uniaxial tension were defined by two equations (10, 11).

\[ \frac{\sigma}{f_t} = 1.20(\varepsilon/\varepsilon_p) - 0.20(\varepsilon/\varepsilon_p)^6 \]  \hspace{1cm} (10)
\[ \frac{\sigma}{f_t} = \varepsilon/\varepsilon_p)/ \alpha((\varepsilon/\varepsilon_p)-1)^\beta + ( \varepsilon/\varepsilon_p) \]  \hspace{1cm} (11)
\[ \alpha = 4\times10^{-6}x^2-0.0019x+0.2775 \]  \hspace{1cm} (12)
\[ \beta = 2\times10^{-5}x^2-0.0087x+2.9249 \]  \hspace{1cm} (13)
\[ X = E^{1.5} \times RI^{0.25} \]  \hspace{1cm} (14)

Where \( E \) is Youngs Modulus of the material and the RI is the Reinforcement Index.
\( \sigma \) - Tensile stress (N/mm\(^2\))

\( f_t \) - Peak tensile stress (N/mm\(^2\))

\( \varepsilon_p \) - Peak tensile strain; \( \varepsilon \) - tensile strain

\( \alpha \) - coefficient ; \( \beta \) - coefficient

**Fig. 4.20 Comparison of Tensile stress-strain curves with EMIS model**

The stress-strain response of the EMIS model has evidently shown that, the pre-cracking behavior was initiated by nearly linearly elastic response followed by non-linear plastic strain until the ultimate stress was reached. The uniqueness of the present model is the simulation of tension softening response achieved without convergence problem. Out of the models studied the EMIS model proves to be more appropriate than any other model. In this paper. The experimental results are analysed and correlated with the Xia and Chin model\(^{84}\). (Fig. 4.20 shows the correlation between theoretical and experimental) results. The regression constants \( \alpha \) and \( \beta \) have been expressed as a function of fibre reinforcement index \([V_f l/f_d]\) and other material parameters.

Also relationship between the density ratio of RPC and Reinforcement Index is derived with respect to Ultimate stress and Elastic modulus.
\[ X = DR^a \times RI^b \]  
\[ f_{u,t} = 1.5305X + 6.8553 \]  
\[ E = 1.1446X + 21.059 \]

Where DR is the density index and RI is the reinforcement index, \( f_{u,t} \) is the ultimate tensile stress in tension and \( E \) is the youngs modulus.

4.2.6.2 Micro-Mechanical Modelling for post cracking behavior of RPC in Tension

The improved mixing techniques and the development of efficient dispersing agents make it possible now to add considerably more fibres than before. The high strength matrices are mainly governed by dense particle systems which are known to improve the interfacial fibre-matrix bond strength remarkably. However, these matrices also show increased brittleness which makes it difficult (almost impossible) to provide them with satisfactory pseudo ductility by means of fibres. Therefore, when the matrix interfacial bond strength is increased brittleness is too high to ensure pseudo-ductility when low aspect ratio \((L_f/d_f)\) high – stiffness fibres such as steel fibres are applied. A micro-mechanical model which is adopted by Li and Leung (which is adopted in VEM modelling by VOO.J.Y.L. et al., (2003)) is adopted in the present analysis to evaluate the multiple cracking and post-cracking behavior of Ultra High Performance concrete.

The effect of fibres in cementitious materials is most pronounced during cracking. The fibres that cross a crack still transfer stresses even though the crack is significantly open. In a deformation controlled uniaxial tension test, the complete bridging stress-crack opening
relationship \( (\sigma_b-w) \) may be observed after the deformation localize in a crack. The area under this curve is the fracture energy \( G_f \) of the material. The initial part of the \( \sigma_b-w \) curve includes both a decreasing aggregate along their shortest embedment length, they start to slip out of the matrix under decreasing stresses. The possibility rupture is governed by the critical fibre length \( L_{cr} = 0.5d_f\sigma_{lu}/\tau \) of fibre.

A simple micro-mechanical shear lag model is adopted to predict the behavior of a fibre being pulled out of a matrix material. The behavior of a single fibre is transferred into a continuum by means of statistical methods, where the position and the orientation of a fibre is assumed to be uniformly distributed. The bridging stress originating from the fibres is given analytically as a function of the crack width.

\[
\frac{\sigma_f}{\sigma_{pc}} = \begin{cases} 
\frac{2\sqrt{\hat{w}}}{\hat{w}^*} & 0 \leq \hat{w} \leq \hat{w}^* \\
\left(1 - \left(\frac{\hat{w}}{\hat{w}^*}\right)^2\right)^{-\frac{1}{2}} & \hat{w}^* \leq \hat{w} \leq 1 
\end{cases}
\] (18)

Where the \( \hat{w} = 2w/L_f \) and the normalised crack width \( \hat{w}^* \), corresponding to the \( \sigma_b-w \) relationship, and \( \sigma_{pc} \) are defined by

\[
\hat{w}^* = \frac{2\tau_{lf}}{(1+\varepsilon_{lf}d_f)} , \quad \sigma_{pc} = \frac{E_fV_f}{E_m(1-V_f)} \frac{L_f}{d_f} 
\] (19)

![Fig. 4.21(a)](image1.png)  ![Fig. 4.21(b)](image2.png)
Fig. 4.21(c) Experimtal \( \sigma_b/\sigma_{cr} \) – \( w \) curves for various volume ratio of fibres (Vf)

Note: the tensile stresses normalised with respect to \( \sigma_{cr} \) equal to 4.18 MPa.

Where \( g \) is the snubbing factor (\( \geq 1 \)) which takes into account that the pull out astrength of a single fibre increases when it is inclined to the crack plane normal.

In the present series a total of seven different RPC mixes were tested with at least three repetitions for each mix. The fibre content range between 1% to 3%. This gives an experimental range of fibre Reinforcement Index \( Vf(Lf/dl) \) from 3.5 to 10. The stress-strain relationship obtained from the experimental values follow an ascending branch which is almost linear until cracking starts. A small load drop is registered at first cracking as the fibres take over the matrix stresses followed by increasing bridging stresses until complete debonding and fibre pull-out. In order to compare between different mixes, each observed stress-strain relationship is composed into a \( \sigma_b – w \) relationship after the first crack occurs. This is due to the assumption that all deformations after cracking are localized in a single crack. Thus, the post-crack strains are multiplied by the LVDT measuring length.
(50mm) to obtain crack widths and the elastic deformations of the uncracked part of the specimen were subtracted (Fig. 4.21 a-c).

**Fig. 4.22(a)**

**Fig. 4.22(b)**

**Fig. 4.22(c)**

**Fig. 4.22(d)**

**Fig. 4.22(a-d) Comparison of Experimental values with micro-mechanical model**

A Cook-Gorden effect is included in the micro-mechanical model. This effect takes into account that a fibre is already debonded over a considerable length just before a crack tip reaches it. This is due to the stress field right in front of the crack tip. The pre-debonded length is termed the Cook-Gorden parameter. By looking at **Fig. 4.22 (a-d)** it is assured that this value has the correct magnitude for the
experimentally observed crack openings corresponding to the post-crack strength. Therefore, it seems that the theoretical behavior of \( w' \) in (Equ. 18) is inadequate to model situations with high contents of steel fibres.

A reverse calculation is performed on the RPC results where \( \sigma_{pc} \approx 6v_f(L_f/d_f) \) MPa from the experimental observations. We have that \( G_{deb} = 5 \sigma_{pc}w'/\sigma_{pc}w' \geq 10G_{tip} = 1kN/m \) from \( (G_{deb} \geq 10G_{tip}) \). Furthermore, it is assumed that this condition is only just fulfilled when the fibre reinforcement index is \( V_f(L_f/d_f) \approx 1 \), which gives \( w' \approx 0.2 \) mm. By looking at Fig. 4.22 a-d it is assured that this value has the correct magnitude for the experimentally observed crack openings corresponding to the post-crack strength. Therefore, it seems that the theoretical behavior of \( w' \) in (Equ. 18) is inadequate to model situations with high contents of steel fibres;

4.3 STUDY OF FLEXURAL PROPERTIES OF RPC

4.3.1 Need for the Present Study

Experimental investigations were carried out to study the flexural strength toughness characteristics of high strength steel fibre reinforced concrete specimens.

Fig. 4.23 Beam Specimen Schematic Diagram
The test method adopted was in line with JCI-S-001-2003 and RILEM TC-162-TDF Draft Procedure-2000 for the determination of flexural toughness and fracture energy of concrete from the load-CMOD (crack mouth opening displacement) curves of notched beams under three-point loading.

A Universal testing machine furnished with closed-loop control based was used with control under displacement of the crosshead. Care was taken to confirm that no unstable failure occurred particularly after the peak load by using a slow rate of 0.05 mm/minute. Subsequently a displacement rate of 0.2 mm/minute was used. **Fig.4.23** shows the schematic diagram of loading scheme.

![Fig.4.24 Schematic Diagram of Loading Scheme](image)

Both the supports were hinged supports having rollers as shown in the schematic diagram **Fig.4.24**. The supports were horizontally movable to avoid any restraint on the deformation until the specimen completely ruptures.

The load was measured using a load cell with an accuracy of 1% of the estimated peak load or better and fixed to the testing machine. The
CMOD was measured using a clip gauge that is capable of measuring to complete rupture of the specimen with an accuracy of 1/1000 m. The thickness of the knife edges to which the clip gauge was attached was less than 5mm. **Fig. 4.25** shows the photographic view of the test set-up used.

![Photographic View of the Test Set-Up Used](image)

**4.3.2 Testing Methodology**

The following test procedure was adopted

a) The specimen was set on its side with respect to its position as molded so that the notch would be located on the bottom.
b) The specimen was continuously loaded without shock at 0.05 mm/minute until the specimen reaches the peak load and the load starts dropping. Thereafter, a rate of 0.2 mm/minute was adopted till the CMOD reaches 3.5 mm when the test is terminated.

c) The load, midpoint deflection and CMOD were continuously measured from the beginning of testing until the specimen completely ruptures or CMOD reaches the maximum value of 3.5 mm. The intervals between readings by a digital measuring device shall be short enough to permit 20 or more readings before the peak load is reached.

e) Tests are regarded as stable when the load and CMOD change slowly throughout the test without abrupt jumps. Results of tests that involve any unstable phenomenon are discarded.

The width (b) and height (h) of the broken ligament are measured to the nearest 0.2mm at two locations. The fracture energy and load-CMOD curve are expressed as averages of at least four Specimens.

4.3.3. Results and Discussions

4.3.3.1 Fracture energy

The fracture energy is calculated by the following equation.

\[ GF = \frac{W}{A_{\text{lig}}} \]

Where,

\( GF \) = fracture energy (N/mm²)

\( W \) = area below CMOD curve up to rupture of specimen (N-mm)

\( A_{\text{lig}} \) = area of broken ligament (b*h) (mm²)
4.3.3.1.(i) First Crack strength

As seen from Table 4.4, the first crack load for RPC specimens (reckoned as stress at CMOD of 0.05mm) ranged from 11.3 MPa (RS2L-2% volume,13 mm fibre) to 18 MPa (RD32- cocktail of 3% -6mm and 2%-13 mm) in case of RPC specimens indicating the effectiveness of fibre combinations. Shorter fibres of 6mm were more effective in increasing the first crack stress compared to 13 mm fibres due to greater number of fibres in the micro crack domain, which effectively restrain the widening of such cracks.

4.3.3.1.(ii) Peak stress

The peak stress for plain RPC was 6.6 MPa. The plain RPC failed immediately after reaching the peak load as the test was carried out under deflection control and not under CMOD control. The peak stress occurs within a CMOD of 0.5mm in case of lower fibre contents and in case of hybrid fibres it occurs at CMOD of about 1mm. The peak stress ranges from 19.8 MPa to 30.2 MPa for RPC beams.

4.3.3.1.(iii) Residual Tensile Stress

The residual flexural tensile stresses at different CMODs are shown in Table 4.4. The reserve strength in the material at even very high CMOD in RPCs is a remarkable feature.

4.3.3.2 Toughness indices

The toughness index defined as the ratio of area of load-CMOD curve given by the following expression (as in case of ASTM 10118 but
modified by considering CMOD in lieu of deflection). Fig.4.26 shows the idealized Load-CMOD curve for elasto-plastic material.

![Idealized Load-CMOD Curve for Elasto-Plastic Material](image)

**Fig.4.26 Idealized Load-CMOD Curve for Elasto-Plastic Material**

\[ I_n = \frac{\text{Area OABB1} - \text{Area OAA1}}{\text{Area OAA1}} \]

Fig.4.27, show the load Vs CMOD plots for reactive powder concrete. The toughness index I100 ranges from 70.9 to 195.3 for RPC beams indicating the superior toughness of RPC.
Table 4.4 Residual Flexural Strength, Fracture Energy and Toughness Indices Different Types of RPC Beams

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Specimen No.</th>
<th>RFTS (N/mm²)</th>
<th>Toughness Index (I)</th>
<th>Gf (N/m m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.05 0.5 1.5 2.5 3.5</td>
<td>20 60 100 140</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>R0</td>
<td>0.00 0.0 0.0 0.0 0.00</td>
<td>0.0 0.0 0.0 0.00</td>
<td>0.02</td>
</tr>
<tr>
<td>2</td>
<td>RS2</td>
<td>16.6 19.8 13.4 8.5 5.8</td>
<td>18.9 50.4 70.9 83.0</td>
<td>6.1</td>
</tr>
<tr>
<td>3</td>
<td>RD21</td>
<td>10.8 26.2 24.2 20.8 17.9</td>
<td>36.6 120.9 195.3 259.2</td>
<td>10.7</td>
</tr>
<tr>
<td>4</td>
<td>RD32</td>
<td>18.0 29.0 30.2 27.4 24.2</td>
<td>23.8 80.5 134.9 183.5</td>
<td>13.0</td>
</tr>
<tr>
<td>5</td>
<td>RS2L</td>
<td>11.3 17.2 12.8 8.4 5.8</td>
<td>22.7 68.9 99.4 119.4</td>
<td>5.6</td>
</tr>
<tr>
<td>6</td>
<td>RS3L</td>
<td>14.3 25.7 26.9 25.2 21.2</td>
<td>24.6 84.8 143.7 195.6</td>
<td>11.6</td>
</tr>
</tbody>
</table>

4.3.3.3 Fracture Energy

The fracture energy computed up to a CMOD of 3.5mm ranged from 5.6 N/mm to 13 N/mm for RPC beams.
4.4 STUDY OF SHEAR PROPERTIES OF RPC BEAMS

Experimental investigations were carried out to study the shear strength characteristics of High Strength Steel Fibre Reinforced Concrete Specimens. RPC beams of size 70 x 70 x 175 mm with different types of fibres [l/d (mm), 6/0.16, 13/0.16] single or in combination and different volume fractions were prepared and tested. The notched specimen used for Flexure is cut at the notch and used as shear specimen. The details of the experimental investigations are presented below.

4.4.1 Test program

The RPC beams are tested for shear by a unique test set up developed at CSIR- SERC, Chennai. The test up simulates a double shear failure for beams at 1/3 rd of loading as shown in Fig.4.28 and Fig.4.29 tested for shear in universal testing machine. Dial gauges were used to measure the deflections as shown in the test up.
Fig. No. 4.22 Double Shear Test Facility for RPC
4.4.2 Results and Discussions

The failure pattern of the RPC specimens tested under Double Shear is shown in Fig. 4.30 (a-f). The shear stress for various fibre dosages are tabulated in Table 4.5. The maximum shear stress is achieved for mixed fibre ratio (3% 6mm+2% 13mm) 83.33 MPa. However, there is a significant increase in shear stress for 2% 13mm fibres (53.09 MPa). Even 3%13mm fibres reported a maximum of 80.43 MPa. It shows the shear stress is increased with increase in fibre content. It confirms with the results of other mechanical tests. Also the minimum shear stress is for the RPC beam without any fibre (13.33 MPa). This shows the impact of addition of high tensile fibres in RPC concrete. Fig. 4.31 shows the Shear stress-Deformation curves for various dosages of fibred in RPC mix. The results confirm that the addition of 2% 13mm fibre dosage is optimum for RPC concrete.
Table 4.5 Shear Properties of RPC Beam Specimens

<table>
<thead>
<tr>
<th>Sl.No.</th>
<th>Fibre content %</th>
<th>Peak Load(kN)</th>
<th>Corresponding Shear Stress(MPa)</th>
<th>Corresponding Elongation(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6mm</td>
<td>13mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R0</td>
<td>0</td>
<td>0</td>
<td>89.25</td>
<td>13.33</td>
</tr>
<tr>
<td>RS2</td>
<td>2</td>
<td>0</td>
<td>238.2</td>
<td>27.18</td>
</tr>
<tr>
<td>RD21</td>
<td>2</td>
<td>1</td>
<td>274.0</td>
<td>46.57</td>
</tr>
<tr>
<td>RD32</td>
<td>3</td>
<td>2</td>
<td>420.0</td>
<td>83.33</td>
</tr>
<tr>
<td>RS2L</td>
<td>0</td>
<td>2</td>
<td>275.0</td>
<td>53.09</td>
</tr>
<tr>
<td>RS3L</td>
<td>0</td>
<td>3</td>
<td>389.15</td>
<td>80.43</td>
</tr>
</tbody>
</table>

Fig. 4.30 Failure pattern RPC beams under double shear
Fig. 4.31 Shear stress-Elongation curves for various dosages of fibres