CHAPTER 1.

Concept of Fiber Reinforced Concrete
Various steel fiber geometries

a. Straight Slit Sheet or Wire
b. Deformed Slit Sheet or Wire
c. Crimped-End Wire
d. Flattened-End Slit Sheet or Wire
e. Machined Chip
f. Melt Extract

TOTAL 184
• Fiber reinforced concrete (FRC) is concrete made of hydraulic cements containing fine or fine and coarse aggregate and discontinuous discrete fibers (ACI 544.1R).

Note:
• Continuous meshes, woven fabrics and long rods are not considered to be fibers.
Definition of fiber

• Fibers have been produced from steel, plastic, glass and natural materials in various shapes and sizes.

• A convenient numerical parameter describing a fiber is its **ASPECT RATIO**, defined as the fiber length divided by an equivalent fiber diameter.

• (Equivalent fiber diameter is the diameter of a circle with an area equal to the cross-sectional area of the fiber). Typical aspect ratios range from about 30 to 150 for length dimensions of 6.4 to 76 mm.
• **Round steel fibers** are produced by cutting or chopping wire, typically having diameters between **0.25 to 0.76 mm**.

• **Flat steel fibers** having typical cross-section ranging from **0.15 to 0.41 mm in thickness** by **0.25 to 0.90 mm in width** are produced by shearing sheets or flattening wire.
• Crimped or deformed fibers have been produced both full length and crimped or bent at the ends only.

• Fibers have been collated with water soluble glue into bundles of 10-30 fibers to facilitate handling and mixing.
• Steel fibers are also produced by melt extracion process.
• This method uses a rotating wheel that touches a molten metal surface, lifts off liquid metal and rapidly freezes it into fibers which are thrown off by centrifugal force.
• The fibers have an irregular surface and a crescent shaped cross-section.
• **Typical glass fibers** have diameters of 0.005 to 0.015 mm, but these fibers may be bonded together to produce glass fiber elements with diameters of 0.013 to 1.3 mm.
Glass – polyester-asbestos fibers
• Typical plastics such as nylon, polypropylene, polyethylene and polyester have been made into fibers with diameters of 0.02 to 0.38 mm.

• Fibers processed from natural materials like asbestos and cotton provide a wide range of sizes.

• Several properties of various fibers are listed in Table 1.1.
Table 1.1 Typical properties of cement-based matrices and fibers.

<table>
<thead>
<tr>
<th>Material or fiber</th>
<th>Relative density</th>
<th>Diameter or thickness (microns)</th>
<th>Length (mm)</th>
<th>Elastic modulus (GPa)</th>
<th>Tensile strength (MPa)</th>
<th>Failure strain (%)</th>
<th>Volume in composite (%)</th>
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<tbody>
<tr>
<td><strong>Mortar matrix</strong></td>
<td>1.8-2.0</td>
<td>300-5000</td>
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<td>10-30</td>
<td>1-10</td>
<td>0.01-0.05</td>
<td>85-97</td>
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<td>10 000-20 000</td>
<td>--</td>
<td>20-40</td>
<td>1-4</td>
<td>0.01-0.02</td>
<td>97-99.5</td>
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<td><strong>Aromatic</strong></td>
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<td>10-15</td>
<td>5-continuous</td>
<td>70-130</td>
<td>2900</td>
<td>2-4</td>
<td>1-5</td>
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<td><strong>Polyamides</strong></td>
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<td></td>
<td></td>
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<td><strong>Asbestos</strong></td>
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<td>0.02-30</td>
<td>5-40</td>
<td>164</td>
<td>200-1800</td>
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<td><strong>Carbon</strong></td>
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<td>3-continuous</td>
<td>30-390</td>
<td>600-2700</td>
<td>0.5-2.4</td>
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<td>900-1000</td>
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<td><strong>Polyethylene:</strong></td>
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<td><strong>PE pulb</strong></td>
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<td>&gt;4</td>
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<td>300-500</td>
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<td>continuous</td>
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<td>300-500</td>
<td>10</td>
<td>5-10</td>
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<td><strong>Polyvinyl alcohol</strong> (PVA, PVOH)</td>
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<td>3-8</td>
<td>2-6</td>
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<td>700-1500</td>
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<td>2-3</td>
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<td>200</td>
<td>700-2000</td>
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<td>0.5-2.0</td>
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Historical Background

• Fibers have been used to reinforce brittle materials since ancient times; straws were used to reinforce sunbaked bricks, horse hair was used to reinforce plaster and more recently, asbestos fibers are being used to reinforce Portland cement.

• Patents have been granted since the turn of the century for various methods of incorporating wire segments or metal chips into concrete.

• The low tensile strength and brittle character of concrete have been bypassed by the use of reinforcing rods in the tensile zone of the concrete since the middle of the 19th century.
Reinforcement bars
• The research by Romualdi & Batson and Romualdi & Mandel on closely spaced wired and random fibers in the late 1950s and 1960s was the basis for a patent based on fiber spacing.

• The Portland Cement Association (PCA) investigated fiber reinforcement in the late 1950s.

• Another patent based on bond and aspect ratio of the fibers was granted in 1972.
• In the early 1960s, experiments using plastic fibers in concrete with and without steel reinforcing rods or wire meshes were conducted.

• Experiments using glass fibers have been conducted in USA since the early 1950s as well as the UK and Russia.

• Applications on fiber reinforced concrete have been made since the mid 1960s for road and floor slabs, refractory materials and concrete products.
• The methods of mixing, placing, consolidating and finishing for SFRC have been developed to a reasonable degree, particularly for pavements.

• The greater difficulty in handling SFRC requires more deliberate planning and workmanship than establishing concrete construction procedures.

• The volume and type of fibers selected determine the maximum aggregate size and volume of paste.

• With these factors known, the techniques of good concrete proportioning can be applied to obtain workable and economical mixes.
• For **glass fibers**, the major experience has been with the **spray-up process** in which the glass fibers and a cement-rich mortar are sprayed simultaneously onto a surface.

• The material is then **compacted** by the use of roller or vibrating trowels to remove air and consolidate the composite.
CHAPTER 2

Fiber Types
Physical & Chemical Properties of Fibers
Asbestos cement

• Asbestos cement is familiar as very low cost roofing and classing material which has had excellent durability during the past 100 years.

• A reason for its success is the great durability of asbestos fibers.

• Studies have been shown that the strength of fiber bundles vary between 400 MPa and 1400 MPa irrespective of exposure up to 7 years.
• The *proportions by weight* of asbestos fiber is normally between 9 to 12% for flat or corrugated sheet, 11 to 14% for pressure pipes and 20 to 30% for fire resistant boards, and the binder is normally a Portland cement.

• *Fillers* such as finely ground silica at about 40% by weight may also be included.

• A *typical tensile stress-strain* (load-deformation) curve for a commercial product is shown in Figure 2.1 where the failure strain is about 2000 x 10^{-6}.
Figure 2.1 Typical stress-strain diagram for FRC.
• No cracks were visible before failure on this FRC.

• Statistics have been shown a rapid decrease since 1980 in UK in sales of asbestos cement sheeting products partly due to well-publisized health hazards associated with asbestos fibers.

• Another significant problem is that the material is brittle and the impact strength is low so that there are a number of deaths every year as a result of people falling through roofs.
Glass-reinforced cement (GRC)

- It is normally made with alkali-resistant glass-fiber bundles combined with a matrix consisting of ordinary Portland cement plus inorganic fibers.

- E-glass fibers have been used with a polymer modified cement matrix to protect glass against attack by the *alkalis in the cement*. 
glass fibre reinforced concrete
Polymer-fiber-reinforced cement

- The inclusion of polymer fibers into cement based products is potentially a very large world wide market.

- Polypropylene and polyvinyl alcohol have been the most used although polyethylene pulb is also used in some thin sheet products.
Polymer fibers in flexible concrete
Polypropylene

Chopped polypropylene films:

- They have been used at fiber volumes of 3% to 5% to produce *alternative products to asbestos* cement with some modifications being required to the traditional machinery.

- The polypropylene in this case gives elastic modulus of 9 to 18 GPa with tensile strengths from 500 to 700 MPa and ultimate strain of 5 to 8%.

- The film is chopped into lengths of 6 to 24 mm to give fibers a rectangular cross-section.
Polypropylene

*Continuous opened polypropylene networks:*

- Layers of networks of continuous polypropylene films as shown in Figure 2.3 with similar properties to the chopped films have been used in fine-grained cement materials to produce alternative products to asbestos cement.
• The **advantage** of this system is that the full fiber strength is used because there is no pull-out and excellent mechanical bonding is achieved by virtue of the uneven micro and micro-slits in the films and the many fine hairs produced in the production process.

• **Bonding strengths** in excess of 40 MPa and **tensile strengths above 25 MPa** have been measured at aligned film volumes of about 9%.
Figure 2.3 tensile stress-strain curves for cement sheet reinforced with polypropylene networks at two fiber volumes.
**Polyvinyl alcohol (PVA) fibers:**

- High strength and stiffness PVA fibers are used widely as an asbestos replacement in asbestos products.

- The fibers are treated on the surface to enhance their compatibility with the matrix, the quantity of fibers being typically **3% by volume**.

- Alkali resistance has been stated by the manufacturers to be excellent and the fibers can survive exposure to temperature of **150°C** without loss in strength.
Polyethylene Pulb

• They are made from short fibers and has been used as a cement retention and drainage aid as a substitute for asbestos fibers in the manufacture of thin sheet products.

• Volume of fibers \((V_f) \leq 12\%\)

• **Improvements**: Flexural strength, ductility, durability (do not swell in the presence of water).
Natural Fibers in cement

• The use of natural cellulose or vegetable fibers in cement or mortar products is common in both developing and developed countries.
Wood fibers

- In developing countries the bulk usage is for wood cellulose fibers from trees.

- The wood is mechanically and chemically pulped to separate the individual fibers which may be between 1 mm and 3 mm long and up to 45 microns in width.

- The fibers are cheap compared with most man-made fibers, they are renewable resource, there is considerable experience in the use of such fibers in existing plant for asbestos cement and they have an adequate tensile strength for cement reinforcement.
• Wood cellulose fibers can be used to produce boards (sheets).

• They are **not suitable for use in bulk concrete** applications because of difficulties in mixing and compaction and their use is therefore limited to automated factory process.
Vegetable fibers

- The use of vegetable fibers in developing countries is generally aimed at producing cheap but labour-intensive locally constructed cement-based roof sheeting often of corrugated or folded plate design.

- **Length** of fibers may be up to **1 meter or more** and are hand placed in a matrix of sand and cement.

- Corrugated sheets of up to 2 meter by 1 meter in size of 6-10 mm thickness and **tiles** may be produced with fibers in preferential directions.
• The cracking stress and strength of the composites are not greatly increased compared with the unreinforced matrix but the fibers enable the sheets to be formed in the fresh state and handled and transported in the hardened state.

• Considerable hardness is achieved in the short term although embrittlement can occur in the long term.

• Long fibers include banana leaves, bamboo, palm, pineapple leaf, sisal, sugar cane, musamba, jute, coir, etc.
• Bamboo, when split into strips and woven into meshes, has been used as reinforcement for a variety of uses from roads and structures to water tanks.

• Tensile strength (MPa) > 100 (most of fibers)

• Elastic modulus (GPa) = 10-25;

• Toughening, post-cracking performance is high ($V_f = 1.5-3\%$)
CHAPTER 3

Properties of Freshly Mixed & Hardened FRC
Preparation of mixes

• Mixing of FRC can be accompanied by more than one method.

• The choice of method will depend on the job requirements and the facilities available; plant batching, ready mixed concrete or hand mixing small quantities in the laboratory.

• Above all, it is necessary to have a uniform dispersion of the fibers and prevent the segregation or balling of the fibers during mixing.
Segregation/balling

- Segregation or balling during mixing is related to a number of factors. The most important appears to be the aspect ratio.

- The other factors which may affect fiber distribution are:
  - volume percentage,
  - coarse aggregate size/grading/quantity,
  - water/cement ratio,
  - method of mixing.

- Increases in aspect ratio, volume percentage of fibers, size and quantity of coarse aggregates intensify balling tendencies.
• Most fibre balling occurs during the fiber addition process and this can be eliminated by care in the sequence and rate of fibre addition or by the use of bundled (collated) fibers.

• Overmixing or poor mixing proportions also cause balling.
Aspect Ratio

• For uniform mixing, the aspect ratio of round wire flat strip steel fiber should be about 100 maximum.
Volume of fibers

- Steel fiber contents in excess of 2 percent by volume are difficult to mix.
Aggregate size

• Conventional concrete mix proportions can be used but try to use aggregates 9.5 mm or less in size or just sand.
Experience suggests:

• w/c ratios between 0.4 and 0.6
• cement contents of 249 to 430 kg/m³

are required for adequate paste contents to coat the large surface area of the fibers.
Table 3.1 Typical mix proportioning for FRC.

<table>
<thead>
<tr>
<th></th>
<th>MORTAR</th>
<th>9.5 mm max. aggregate</th>
<th>20 mm max. aggregate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (kg/m³)</td>
<td>514-710</td>
<td>350-593</td>
<td>296-530</td>
</tr>
<tr>
<td>w/c ratio</td>
<td>0.3-0.45</td>
<td>0.35-0.45</td>
<td>0.4-0.5</td>
</tr>
<tr>
<td>% of fine to coarse aggregate</td>
<td>100</td>
<td>45-60</td>
<td>45-55</td>
</tr>
<tr>
<td>Entrained air (%)</td>
<td>7-10</td>
<td>4-7</td>
<td>4-6</td>
</tr>
<tr>
<td>Fiber content:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deformed steel</td>
<td>0.5-1.0</td>
<td>0.4-0.9</td>
<td>0.3-0.8</td>
</tr>
<tr>
<td>Smooth steel</td>
<td>1.0-2.0</td>
<td>0.9-1.8</td>
<td>0.8-1.6</td>
</tr>
<tr>
<td>glass</td>
<td>2.0-5.0</td>
<td>0.3-1.2</td>
<td>--</td>
</tr>
</tbody>
</table>

TOTAL 184
Admixtures

• Conventional admixtures are commonly used in FRC for air entrainment, water reduction, workability and shrinkage control.

• Superplastisizers have been found to be useful in producing high quality fibrous concrete with a low w/c ratio and high workability.
Pozzolans

• Such as fly ash (pfa) can be used in fibrous concretes to reduce the relatively high cement contents the same as in conventional concrete requiring a high volume of cementitious materials or they can be added to the mix proportion to increase workability and long-term hardened material properties.

• **25-35% replacement** of cement with fly ash is usually optimum.
• Compared to conventional concrete, FRC mixes are generally characterized by;
  – Higher cement contents
  – Higher fine aggregate content
  – Smaller sized coarse aggregate
Mixing Methods

• Fibers should be dispersed uniformly throughout the mix.

• This can be done before the mixing water is added.

Small Mixes

• For laboratory mixes, shaking the fibers through a wire mesh basket is appropriate.
Large quantity mixes

• Used for batch plants, ready-mixed concrete trucks.
• Feed fibers from a conveyor belt on to the central belt used for carrying aggregates and cement to the mixer.
• Blend fiber and aggregate prior to charging the mixer. Use standard mixing procedure throughout.
• Blend fine and coarse aggregate in the mixer. Then add the fibers at the mixing speed (12 rpm). Lastly add cement and water or cement followed by water and additives.
• Add fibers to previously charged aggregate and water. Add cement and remaining water.
• Add fibers as the last step in mixing.
Mixing Methods

Glass fibers

• They have less tendency to balling. Following procedures can be used:

• For laboratory mixes, shaking through a wire basket is not necessary. The glass fibers can be added directly to the mix containing all the other ingredients including water.

• For batch plant and RMC trucks, the conventional mixing procedures should be followed with the glass fibers added last. They can be dumped directly or chopped or blown into the truck.
Placing

- A fiber mix will generally require **more vibration** to move the mix and consolidate it into forms.
- Properly controlled internal vibration is acceptable but external vibration of the forms and exposed surface is preferable to prevent fiber segregation.
- The fibrous nature of the mix makes the use of shovels or hoes difficult.
- Forks are preferred for handling low slump mixes.
- Standard **screeding** methods are acceptable such as wood screed board, portable vibrator mounted on boards or by mechanical method of the slipform paver and sidewalk paver.

* A wooden or metal templed raised, dropped and pulled along by two concretors, one at each end, to finish the surface of a slab being cast. It is slightly longer than the width of the slab being finished.
Curing

• Fibrous concrete should be cured and protected using same methods and techniques as for conventional concrete.
Testing Fresh FRC

• Standard quality control test methods are being used for FRC (slump, air, density and strength tests).

• However, these tests were developed for conventional concrete and may be misleading.

**Slump**

• Slump of a concrete mix is significantly reduced by steel fibers. Use of *inverted slump cone* test for workability is recommended.
Relationship between slump, Vebe, inverted cone time.

- Maximum-aggregate size = 5/8 in. (14mm)
- Maximum-aggregate size = 1 in. (25mm)

Fiber Length = 3/4 to 1 1/2 in. (19-38mm)
Fiber Volume = 0.75 to 1.5%

TOTAL 184
**Pumping**

- Pumping of steel FRC with up to 1.5% by volume has been done successfully (pipe of diameter 125-150 mm).
- Pumping of glass FRC has been accomplished in both field and precast applications using conventional pumping equipment.

**Shotcrete**

- Shotcreting of steel FRC mixes is routinely done using conventional shotcrete equipment.
1. Glass fiber spray-up

- The spray-up process, utilizing glass fibers is used extensively to produce thin sheet light weight cladding panels for buildings.

- **Method**: Chopped glass fiber and cement slurry are simultaneously deposited into the form and are in effect, mixed at the point of placement.

- **Strength**: Flexural strength = 20-31 MPa with 4-5% by volume fibers on 9.5 mm thick specimens.
Slurry Mixes:

• High cement factors and low w/c ratios.
• Avoid excessive fines in aggregates.
• Natural sands with round particles are recommended (minimizes blockages in spray equipment, makes pumping easier and results in lower water demand and in smoother slurries).
• Cement contents 1187-1350 kg/m³ (very high)
• Type I cement is usually used (particle size results in low w/c ratios).
• w/c ratios: 0.30-0.35
• Admixtures: water reducers (to get low w/c ratios), normal set & set-retarding water reducers (to prolong working time of slurry), superplastisizers (rapid slump loss), accelerating admixtures (not preferred due to pumping problems and shrinkage of final composite).
Curing

• Period of curing should last at least 7 days.
2. Glass fiber precast products

• Glass FRC products have been also produced by incorporating fibers (0.3-5% by volume) at the mixer, followed by typical precast forming methods such as vibration casting and press molding.

• Care must be exercised during mixing to minimize fiber damage and segregation of fibers (balling).

• Length of fiber = 25 mm or less.
3. Surface bonding

• The surface bonding method of masonry construction involves **dry stacking** of concrete blocks for a wall followed by plastering both sides of the wall with a thin skin of glass FR cement or mortar.
Surface bonding-walls

- No mortar between bricks.
- Cover surface of wall with GFR mortar.
• The mixes are usually prepacked and requires only the addition of water.

Curing

• Moist curing of surface for at least 48 hours.
• Can be done by water spraying or plastic sheet cover on the wall.
CHAPTER 4.
Mix proportioning of FRC
For the specified workability and strength, the mix should contain minimum fiber content and maximum aggregate.

The cement paste content depends upon three factors:

- Volume of fibers
- Shape and surface characteristics of fibers
- W/C ratio.
Common SFRC mixes generally have the following range of parameters:

- Cement content: 300-500 kg/m³
- w/c ratio: 0.45-0.60
- ratio of sand to total aggregate: 50-100%
- fiber content: 1.0-2.5%
- fiber aspect ratio (l/d): 50-100
Compared to conventional concrete, some SFRC mixes are characterized by:

- higher cement contents,
- higher fine aggregate content,
- decreasing slump with increasing fiber content.

Conventional admixtures and pozzolans are also used for FRC.

Reasons of using them are:

- Air entrainment
- Water reduction
- Workability control
- Shrinkage control
Balling

• Experience has shown that if the combined fine and coarse aggregate gradation envelopes as shown in Table 4.1 below are met, the tendency to form balls is minimised and workability is enhanced.

• Alternatively, a mixture based on experience can be used for trial mix.
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<th>13</th>
<th>19</th>
<th>25</th>
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</tr>
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<td>0.08</td>
<td>0-2</td>
<td>0-2</td>
<td>0-2</td>
<td>0-2</td>
<td>0-2</td>
</tr>
</tbody>
</table>

TOTAL 184
NOTE:

• Aggregates should be well graded from the largest to the smallest size.

• Aggregates should not vary near the maximum allowable percent passing one sieve to the minimum allowable passing the next sieve.
• The basic aim in mix proportioning is to produce a cohesive and compactable mix which will have enough cementitious matrix to embed the aggregates and the fibers and to avoid bundling of fibers, segregation, bleeding during placing and compaction operation.

• The best way to produce such a mix is to use a little excess of fines and a superplasticizer.
Fines:

• Can be increased by increasing cement content, using inert filler, using pozzolanic filler (pfa, etc).

• Pozzolanic filler will create chemical reaction between pozzolan and mineral components of cement.
Aspects to be considered in correct mix design

• Obtaining the strength and basic engineering properties required to meet structural design requirements of strength, fatigue endurance, etc.

• Constructability to be mixed, transported, placed and finished.
CHAPTER 5.
Mechanical Properties of Fiber Reinforced Concrete & High Strength Fiber Reinforced Concrete
Spacing Concept

• The strength of concrete or mortar with air can be increased by increasing the fracture toughness or decreasing the stress intensity factor at the tip of the internal cracks.
• **Ramouldi & Batson**: To increase the tensile strength, stress intensity factor should be decreased by using closely spaced wires as crack arresters.

• **Snyder & Lankard**: studied on the fiber reinforcement effect upon first crack strength. They used 2% volume of steel fibers. The following expression shows the average fiber spacing:
- $S$: Spacing between centroids of fibers.
- $d$: Fiber diameter.
- $\rho$: Volume percentage of fibers.

\[
s = 13.8 \ d \ \sqrt{\frac{1}{\rho}}
\]
• **McKee** has derived an equation for fiber spacing that is slightly different than the above equation.

• The spacing is given by:

\[
S = 3 \sqrt{\frac{v}{\rho}}
\]

\(v\): volume of a single fiber.
\(\rho\): Volume percentage of fiber in the mortar.
Composite Material Concept

• When a plain mortar or plain concrete beam is subjected to increasing loads, cracking of the tensile zone immediately leads to failure of the beam. However, careful measurements have revealed that a major crack which results in failure of a beam is preceded by slow microcracking growth.

• For FRC, the proportional limit is: the load below which a material is essentially linearly elastic.

• The load-deflection curve is more or less linear up to the proportional limit.
Figure 5.1 Load deflection curve of FRC.

This load limit is also called the “**elastic limit**” or the “**first crack strength**” of the composite
Table 5.1 below shows the proportional limit (A) and maximum load (B) for FRC.

<table>
<thead>
<tr>
<th>Volume of fibers (%)</th>
<th>Proportional limit (MPa)</th>
<th>Maximum load (MPa)</th>
<th>(max. Load/prop. Limit) ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.3</td>
<td>6.3</td>
<td>1.0</td>
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<tr>
<td>4.6</td>
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<td>5.32</td>
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<td>1.90</td>
</tr>
<tr>
<td>7.80</td>
<td>11.0</td>
<td>21.7</td>
<td>1.97</td>
</tr>
<tr>
<td>8.80</td>
<td>12.8</td>
<td>27.3</td>
<td>2.13</td>
</tr>
</tbody>
</table>
• Addition of 4.6% fibers by volume of composite increases the elastic limit only slightly.

• Increasing the volume of fibers increases the proportional limit more or less linearly.
Ultimate Strength & Toughness

• The above load deflection curve (Figure 5.1) is nonlinear beyond Point A and reaches a maximum point at B, the ultimate strength.

• Maximum load is controlled by fibers gradually pulling out, and the stress in the fiber at the ultimate load is substantially less than the yield stress of the fiber.

• After the ultimate load, the decrease in measured load with increasing deformation is much less for FRC than that of plain concrete.
\[ E_{FRC}^N = (10 - 40)E_{Plain Concr}^N \]
• Ultimate strength of FRC is function of $V_f$ & aspect ratio

• If segregation of fibers is avoided, then the increasing volume percentage of fibers more or less linearly increases the strength of the composite.
The ultimate strength of the composite is given by:

\[ S_c = A S_m (1 - V_f) + B V_f \left( \frac{l}{d} \right) \]

- **Sc**: Stress value of composite; **Sm**: Stress value of matrix (mortar or concrete); **l**: length of the fiber; **d**: diameter of the fiber; **A**, **B**: Constants obtained by a plot of composite strength against Vf (l/d) (A_{max}=1.0)
Toughness

• Energy absorbed prior to complete separation of the specimen.

• This can be found by taking the area under the complete tension or compression stress-strain curve or area under the load – deflection curve in flexure.
A = Proportional Elastic Limit, approximates first crack.

**Toughness Indices**

\[ I_5 = \frac{\text{Area OACD}}{\text{Area OAB}} \]

\[ I_{10} = \frac{\text{Area OAEF}}{\text{Area OAB}} \]

\[ I_{20} = \frac{\text{Area OAGH}}{\text{Area OAB}} \]
• Energy absorbed can also be measured by **impact test**.

• **Toughness** = function of (type, volume, aspect ratio, nature of deflection, orientation of fibers)

• **Type**: Steel, polymer, carbon, etc.

• **Nature of deflection**: Flexural or compressive.
Static Strength

- Steel fibers up to about 4% by volume were found to increase the “first crack flexural strength” of concrete up to 2.5 times the strength of unreinforced materials and slightly increased the compressive strength.
• Field placement FRC; $V_f \leq 2\%$ by volume

• **Splitting tensile** strength ($V_f = 3\%$ by volume) = 2.5 times higher than unreinforced mortar
• **Splitting tensile** strength
  \((V_f = 1.5\% \text{ by volume}) = 2.0 \text{ times higher than unreinforced mortar.}\)

• **Direct tensile strength**
  \((V_f = 1.5\% \text{ by volume steel fibers}) = 1.4 \text{ times higher than unreinforced concrete}\)

Dynamic Strength

• The dynamic strength of concrete reinforced with various types of fibers and subjected to explosive charges, dropped weights, and dynamic tensile and compression loads have been measured.

• Dynamic Strength of FRC = 5-10 times higher than of unreinforced concrete.
• The greater energy requirements to strip or pull-out the fibers provides the **impact strength** and the resistance to spalling and fragmentation.

• An impact test has been devised for FRC which uses a 4.5 kg hammer dropping onto a steel ball resting on the test specimen (see Figure 5.3 below).

• For, RFC, the number of blows to failure is typically several hundred compared to 30 to 50 for plain concrete.

Figure 5.3 Impact test apparatus developed for FRC (Ö. Eren, 1999, PhD thesis, EMU)
Fatigue Strength

• Two types of failure can take place in concrete.

• In the first, failure occurs under a sustained load (or slowly increasing load) near, but below, the strength under an increasing load, as in a standard test; this is known as static fatigue or creep rupture.
• The **second** type of failure occurs under cyclic or repeated loading and is known simply as **fatigue**.

• Extensive experimental fatigue studies have been conducted on steel fiber reinforced mortar and concrete beams.

• In general, for a given fiber type, *there is a significant increase in fatigue strength with increasing percentage of steel fibers.*
• It has been shown that the addition of fibers to conventional reinforced beams increases fatigue life and decreases the crack width under fatigue loading.
Creep

• The limited test data indicate that wire fiber reinforcement has **no significant effect** on the creep behaviour of Portland cement concrete.
Corrosion of steel fibers

- An early study showed *insignificant corrosion* by salt water on Portland cement mortar reinforced with 2% by volume steel fibers and no change in flexural strength was observed up to 90 days of rotation in and out of saturated salt water solution.
Another test of steel fiber concrete durability at show minimal corrosion of fibers and no adverse effect on the flexural strength after 7 years exposure to deicing salts.

The high chloride content did not cause corrosion of fibers at or near exposed surfaces.
• Another research showed that compressive strength loss of FRC was measured to be 15% after 10 years exposure in sea water.

• Plain mortar showed 40% loss in compressive strength after 10 years exposure in sea water.
Thermal Conductivity

• Thermal conductivity of steel fiber reinforced mortar with 0.5% to 1.5% by volume of fiber at atmospheric pressure showed small increases with increasing fiber content.

• Another work indicated 25 to 50% increase in thermal conductivity for concrete with 1 to 2% by volume of steel fibers.

• Much larger increases were found for copper fibers (a factor of 4 for 4% by volume of fibers).
Abrasion Resistance

• A research in USA shows that samples with 2.5% by volume of fiber reinforced and plain concrete were tested, using a modified NBS wear testing machine, abraded to a depth 27% less than plain concrete with gravel.

• Tests by the Corps of Engineers suggest that abrasion resistance of steel FRC against scour from all types of debris contained in water flowing through and over structures is not improved over that of plain concrete.

• The quality and hardness of aggregate determine the rate of erosion.

Friction & Skid Resistance

• Static friction, skid and rolling resistance of FRC and identical plain concrete laboratory slab samples were compared in a simulated skid test.

• FRC had 9.5 mm maximum aggregate size.
Result indicated following:

- Static friction for dry concrete surfaces was independent of the steel fiber content.

- Abrasion and erosion of the surface of FRC had up to 15% higher and rolling resistance than plain concrete under dry, wet and frozen surface condition.
NOTE:

- **Friction**: The force that makes it difficult for an object to slide over something.

- **Skid**: If a vehicle skids, it slides sideways while moving, for example if you are trying to stop it suddenly on a wet or icy road.
High Strength Steel Fiber Reinforced Concrete (HSSFRC)
Introduction

• The main disadvantage of high-strength concrete is its highly **brittle behavior** and this can be overcome by adding fibers to concrete.

• This would also improve some other **mechanical properties** of high-strength concrete such as impact resistance, surface abrasion resistance, splitting tensile strength and compressive strength.

• These properties are not very well known for high-strength steel fiber reinforced concrete (HSFRC) yet.
• **silica fume** is no longer a waste by product from the silicon metal and ferrosilocon alloy industries, but a well-established pozzolanic material which contributes unique properties of Portland cement products.

• **Silica fume modifies** physical characteristics of fresh cement paste as well as the microstructure of the paste after hardening.
• Steel fiber reinforced concretes incorporating silica fume benefit from the improvements imparted to plain concrete, including:

  – increased cohesiveness and reduced segregation tendencies;
  – reduced permeability resulting from the decrease in the number of coarse particles in the cement paste incorporating silica fume,
  – Reduced permeability leads to enhanced durability of the material;
• the potential for developing very high strengths;

• Increased sulfate resistance and reduced alkali aggregate reactivity.

• High strength fiber reinforced concrete can be an alternative for use in pavements, overlays, slabs, grades and other such applications.

• However this applications require the concrete to be more resistible to abrasion and impact.
Practical Applications of HSFRC

• HSFRC has higher strengths in flexure, fatigue, impact and resistance to spalling.

• These characteristics lead to thinner concrete sections such as airport pavements and industrial floors, improved surface quality and reduced maintenance.
Concrete Pipe

The advantages from the use of steel fibers in concrete for pipes include:

1. improved performance,
2. thinner wall sections,
3. strengthening the whole volume of concrete including extreme edges,
4. reduced possibility of accidental damage during handling.

- Non-pressure pipes have been produced using most of the standard pipe making methods although there are some questions related to the economical advantages.
Structural Units

• The advantage of fiber involvement in this type of application include:
  – increased crack resistance,
  – ductility at failure,
  – higher load capacity, and
  – a thinner concrete section (for reduced dead load).

• SFRC has been considered as a structural element in bridge decks.
**Slabs**

- Precast slabs approximately 1.1 m$^2$ and 65 mm thick supported by a tabular steel space frame to give a de-mountable car park at London airport and this has performed very well since 1971.

- *Wire content was 3% weight of 0.25 mm diameter by 25 mm in length fibers in a mix with 10 mm maximum size of aggregate.*
Industrial Floors

- One method to improve the resistance of concrete when subjected to impact and/or impulsive loading is by the incorporation of *randomly distributed short fibers*.

- The increase in impact strength at full failure was found to be 730% for concretes with 2% fiber content compared to plain concrete.

- Industrial slabs are applications which can take the increased impact resistance and post-cracking ductility of SFRC.
Industrial floor
Hydraulic Structures

• SFRC has the advantage and benefit to resist *cavitation, erosion, and impact* damage in hydraulic structures such as sluice ways and spillways accompanied with dams applications in the US (Libby dam, Montana, and Damon the Snake River).

• More than 1000 m³ of SFRC was placed, some of it pumped, at fiber volumes varying from 1 to 2 %, and fiber dimensions include 0.25 x 0.56 x 25 mm rectangular fibers and 0.11 x 19 mm long round wires in mixes with maximum aggregate size of 20 mm and 10 mm respectively, also water-reducing and air-entraining agents were used in all cases.
Cavitation-erosion of hydraulic structures
• One researcher reported that the abrasion resistance is enhanced by the addition of silica fume.

• This is believed to be caused by the improved hardness and wear resistance of cement paste itself, as well as the enhanced bonding between the paste and aggregate.
SIFCON

- Slurry Infiltrated Fiber Concrete (SIFCON) is a type of SFRC in which the fibers are preplaced and fluid grout fills in around the fibers in order to fill the section first, and the resulting fiber network is infiltrated by a cement based slurry.

- With this method, up to 25% volume of fibers can be achieved and mechanical properties such as compressive, tensile, flexural and shear strengths, are increased.

- Compressive strength up to 140 MPa, tensile and shear strengths up to 28 MPa, and flexural strength up to 90 MPa have been reported.

- Applications of SIFCON include military defensive fighting positions, blast resistant structures, bridge and pavement repairs.
Highway, Street, and Road Pavement Overlays

• The interest in FRC as an overlay material for the rehabilitation of pavements is very high.

• This is due to the extreme maintenance problems, and the conventional overlay materials do not in many cases provide a satisfactory remedies to the problem.

• Due to FRC's superior properties such as strength and fatigue, also its ability to be placed in thin sections seems to offer many benefits as an overlay material.

• Many projects have been completed involving overlays of highway pavements, residential and urban streets, and parking areas.
Airfields

- Curl (warping) of concrete slabs and related cracking is a common problem in all types of concrete pavements and overlays and is essentially independent of the fibers in SFRC.

- However, the high cement amounts and reduced thickness of SFRC airfield pavements make them very prone to curling.

- This basically related to the properties of the concrete itself, the environment, the construction controls, and the slab dimensions.

- The thin sections of SFRC pavements and wider spacings provides a proper jointing design and construction more critical.
AN OLD AIRFIELD CONCRETE PAVEMENT
• SFRC airfield pavements have been applied in the US, Europe, Australia, India, Taiwan, and Cuba.

• All of the projects in USA were thoroughly and systematically inspected in late 1982 and early 1983, where all of the placements were performing their intended and very little or no maintenance was required.

• However, corners of exposed surface fibers, curling, and cracking were expressed by airport personnel.

• Since then, some routine corner maintenance has become necessary of the high use pavements, and a few of them have developed cracking and curl which may require remedial work.
CHAPTER 6
Measurement of Properties of FRC
Introduction

• The use of FRC has passed from purely experimental laboratory scale applications into factory and field applications involving the placement of many thousands of cubic meters annually throughout the world.

• This has created a need to review existing test methods and develop new methods where required for determining the properties of fibrous concrete.

• If not otherwise noted, other tests commonly run on concrete such as absorption and voids, time of setting and specific gravity are considered acceptable for FRC.
Specimen Preparation

• Test specimens should be prepared by using **external vibration** only.

• **Internal vibration is not desirable** and rodding is not acceptable, as these methods of consolidation may produce fiber orientation and nonuniform samples.
• When necessary, an **external vibration** can be held against the outside of the form to provide consolidation of small specimens.

• The **method, frequency amplitude and time** of vibration should be recorded.

• The **type, size and amount of fiber** should be recorded.

• The **number of tests and coefficient of variation** (standard deviation divided by mean) of test results should be recorded.
Coefficient of variation $= \frac{S}{x}$

S: standard deviation; X: Mean
TESTS
1. **Modulus of Rupture (MOR)**

**ASTM C31** (Practice for making and curing concrete test specimens in the field)

**ASTM C42** (Obtaining and testing drilled cores and sawn beam of concrete)

**ASTM C78** (test for flexural strength of concrete-using simple beam with third point loading)

**ASTM C192** (making and curing concrete test specimens in the laboratory)

**ASTM C293** (test for flexural strength of concrete-using simple beam with center point loading)

**ASTM C683** (test for compressive and flexural strength of concrete under field conditions)

*Number of specimens: At least 3 flexural strength specimens should be tested.*
• **Dial gages and LVDT** (linear variable differential transformers) can be used to obtain deflection values.

• **Load levels** at 1\textsuperscript{st} crack (the point at which the load deflection curve deviates from linearity), at maximum load, and at 1.9 mm of center deflection should be reported (See Figure 6.1).
Figure 6.1 Flexural strength test example.

Third-point Loading
Head of Testing Machine
\[ d = \frac{L}{3} \]

Span Length = L

ASTM C 78 - Third-Point Loading - half the load is applied at each third of the span length. MR is lower than center-point loading. Maximum stress is present over the center 1/3 portion of the beam.

ASTM C 393 - Center-Point Loading - the entire load is applied at the center span. The MR will be greater than third-point loading. The maximum stress is present only at the center of the beam.

Load

A = Proportional Elastic Limit, approximates first crack.

Deflection

\[ \delta \]

TOTAL 184

Toughness Indices

\[
5 = \frac{\text{Area OACD}}{\text{Area OAB}}
\]

\[
10 = \frac{\text{Area OAEF}}{\text{Area OAB}}
\]

\[
20 = \frac{\text{Area OAGH}}{\text{Area OAB}}
\]
Also, the following should be recorded:

- Area under the load deflection curve from the start of the test until maximum load.

- The area under the load deflection curve from the start of the test until 1.9 mm of center deflection.

- The area under the load deflection curve from the start of the test to the point after maximum load where the load is 80% of maximum should be reported.
• This information is used to provide essential data which describes the material’s behaviour in flexure, and to provide information that can assist in design.
Also see the following;

• **ASTM C1018**: Standard test method for flexural toughness and first crack strength of FRC (using beam with 3rd point loading).

2. Impact Strength

- **Importance**: Impact strength is an important property of FRC.

- It demonstrates the *amount of impact energy* necessary to start a visible crack in the FRC and then to propagate or continue *to open that crack*.

- *It can be used to compare the relative merits of different fiber concrete mixes or to demonstrate the improved performance of a fiber mix when compared to conventional concrete mix.*
• **Equipment:**

(1) A standard, manually operated 4.5 kg compaction hammer with an 18-in drop (ASTM D 1557),

(2) A 2.5 –in diameter, hardened steel ball,

(3) A flat baseplate with positioning bracket similar to that shown in Figure 6.2.
Figure 6.2 Impact test equipment developed by Eren, Ö. (1999).
• In addition to the above equipment, a mould to cast **150 mm diameter by 60 mm thick** concrete specimens is needed.
Procedure:

• The specimens can be cut from full-sized cylinders to yield a specimen size of the proper thickness.

• Specimens should be tested at 7, 28 and (if desired) 90 days of age.

• Curing and handling of the specimens should be similar to that used for compressive strength cylinders, but accelerated curing is not desirable.

• The thickness of the specimens shall be recorded to the nearest 1.5 mm.

• The thickness of the sample shall be determined by averaging the measured thickness at the center and each edge of the specimen along any diameter across the top surface.
• The samples are placed on the base plate within the positioning lugs with the finished face up.

• The positioning bracket is then bolted in place and the hardened steel ball is placed on top of the specimen within the barcket.

• The drop hammer is placed with its base upon the steel ball and held there with just enough down pressure to keep it from bouncing off the ball during the test.

• The baseplate is set solidly on a rigid base, such as a concrete floor.

• The hammer is dropped consecutively and number of blows required to cause the first visible crack on the top and the ultimate failure are recorded.
Ultimate failure:

• Number of blows required to open the cracks in the specimen sufficiently so that the pieces of concrete are touching three of the four positioning lugs on the baseplate.
3. Air content, yield and unit weight

- Standard air content test equipment and procedures for conventional concrete can be used for determining the air content, yield and unit weight of FRC.

- The samples should be prepared using external or internal vibration as permitted by ASTM C31 and C192 and not by rodding.
4. Compressive strength

• ASTM or EN compressive strength equipment and procedures used for conventional concrete can be used for FRC.

• External vibrator should be preferred for compaction of FRC.

• The cylinders should be 150 x 300 mm in size (or 150 mm cube).

• Smaller sizes are not advised.
5. Splitting tensile strength

- The splitting tensile strength test (ASTM C496 or BS EN 12390-6) can be used to determine the first crack tensile strength.

- Strain gages (or LVDT) can be used to determine the first crack.
6. Freeze-thaw resistance

- ASTM (ASTM C666) is applicable to FRC.

- Weight loss is not a recommended method for determining the freeze-thaw resistance of FRC because of material that becomes dislodged from the specimen mass, but remains loosely bonded by the fibers.

- The inclusion of fibers should not be considered as a substitute for proper air entrainment to obtain freeze-thaw resistance.
7. Shrinkage

• ASTM test (ASTM C341) for length change of concrete is applicable to FRC.

• It is recommended since the test samples are cut from larger cast concrete samples and the influence on fiber orientation due to casting samples in a smaller molds is eliminated.

• ASTM C157 should not be used unless the specimen is cast in a size that has least dimension that are at least twice the fiber length and three times the maximum aggregate size.
8. Creep

• The current **ASTM C512** test method for creep in concrete is applicable to FRC.
9. Modulus of elasticity

- The current ASTM test (ASTM C469) for modulus of elasticity and poisson’s ratio is applicable to FRC.
10. Cavitation, erosion and abrasion resistance

• As with conventional concrete, testing FRC for cavitation, erosion and/or abrasion resistance (ASTM C418, C779) is extremely difficult, if realistic and practical results are desired.

• Any of these special tests should be carefully evaluated and their specific applicability to a job should be considered in detail.

MEASUREMENT OF ABRASION RESISTANCE

11. Workability

- Basically, workability is considered to be that property of plastic concrete which indicates its ability to be mixed, handled, transported, and most importantly, placed with a minimum loss of homogeneity.

- **Slump test** is not a good indicator of relative workability.

- Especially, this is true and more serious problem for FRC.

- In addition to the **VeBe** and **inverted cone** tests, slump can be used as an indicator of relative uniformity for FRC, but results must be evaluated with caution.
VeBe

• For research and testing in major laboratories, the vebe procedure described in “BS EN 12350-3: Testing fresh concrete-Part 3: vebe test” is an excellent way to determine workability of FRC.

• It is applicable to mortars and concrete and it takes into account the effect of aggregate shape, gradation, air content, admixture effect and surface friction of fibers.

• Vebe test is not convenient in field placements.
Inverted Slump Cone (ISC):

• Developed that uses internal vibration.
• The method requires:
  – A slump cone (ASTM C143)
  – A standard yield bucket (ASTM C129)
  – Internal vibrator (C192) of diameter 1 – 1.5 inches.
• Frequency and amplitude of vibration should be recorded together with diameter of internal vibrator.

**Procedure:**

• The inverted slump mold is loosely filled with concrete without compacting and struck off level at the top.

• The vibrator is started, inserted into the center of the cone and allowed to fall freely to the yield bucket bottom—approximately a few seconds being required for total immersion of the vibrator.

• The vibrator is held vertically with the end of the vibrator just resting on the bottom of the bucket.
• The time from initial immersion of the vibrator to when the slump mold is empty is recorded as the test time.

• Test times can be used to compare FRC to conventional mixes.
CHAPTER 7
COST & ECONOMICAL BENEFITS OF SFRC
Economic Parameters

• There are many and various parameters that enter the economic consideration for FRC products.
Fiber

• The cost of this addition is of the utmost importance.

In fiber economics we must consider:
• the type of fiber,
• the source of manufacturing
• The performance offered.

• Figure 7.1 shows the relationship between slab thickness, concrete cost and fiber cost.
Figure 7.1 Cost relation between slab thickness, concrete and fiber.
• The cost that are not indicated on the curve are as follows:

• The savings of placing of other reinforcing materials with special handling, cut-outs, overlaps, etc.

• The handling of the reduced amount of concrete material.
• Some steel fibers are designed to do a specific job.

• **For example**, shorter, smaller diameter fibers are used in shotcreting.

• The major limiting factor is the inside diameter of the contractor’s **shotcrete equipment hose**.

• Hose inside diameters are generally **37 mm to 50 mm**, so fiber length must be within these dimensions or clogging of the line will result with costly downtime.
Longer length fibers

• They are generally used in other applications. They are preferred due to reduction in cost.
Figure 7.2 Relationship between flexural strength and the $w/\ell/d$ for mortar.
• **From this figure**, it can be seen that if the length increases from 1 to 2 the weight of the fibers can be reduced by $\frac{1}{2}$.

• This is a significant cost savings.

• Unfortunately all fibers do not react the same way during mixing.

• **Special systems** are sometimes used to prevent balling, such as glueing the fibers into bundles which changes the aspect ratio.
• The **longer fibers** will orient themselves in the XY plane more readily than shorter fibers, especially in thin overlays.

• **Overlays 15 mm thick using 50 mm long fibers were placed in a high rise condominium in Miami, Florida.**

• Costs again were greatly reduced due to the efficient use of the fibers in the plane requiring reinforcement.
Location

• Location is also very important.

• This generally determines what materials are available within an economic radius.

• Diego Garcia (an Island), 500 miles of the coast of India, is a forward American base.

• All construction materials must be transported to the island which includes potable water.

• The island averages 1 ½ feet above sea level.

• The use of steel fibers for runway or other constructions can reduce the amount of materials generally by one-half with major cost savings.
• The major strengthening factors allow us to consider such a drastic reduction in slab thickness.

• One is the primary increase in flexural strength of concrete.

• This flexural strength is easily increased by factor of 2.

• The other major factor is the endurance limit of the concrete.

• The increased endurance limit of FRC is as high as 90% of the first crack strength while the endurance limit of normally RC is considered only 50% of the initial cracking strength.
• Flexural strength allow the reduction of the slab on grade to one-half the thickness.

• Therefore, if steel fibers cost less that one cubic yard (1 m³ = 1.3 yd³) of concrete there will be a cost saving in the material used.

• Besides the cost of savings of materials there will be cost of savings in placing standard reinforcement.

• A section of a major highway offers a cost analysis for initial installation and lifetime costs of highway versus asphalt pavement (see Table 7.1 below).
NOTE:

• Endurance limit: In fatigue testing, the maximum stress for any material below which fracture do not occur however many reversals of stress take place.

• *For steels, the endurance limit can be determined at 6-10 million cycles of stress.*

• It is roughly three quarters of the yield point in mild steel.
### Table 7.1 Estimated cost of 1 mile (1.6 km) project

<table>
<thead>
<tr>
<th>Year</th>
<th>Concrete</th>
<th>Asphalt</th>
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<tbody>
<tr>
<td>1</td>
<td>112,000$</td>
<td>90,000 $</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>Seal coat=3 gal/sq yd. X 14080 sq.yd.X0.46$/gal = 1,943$ Aggregate seal=27#/sq.yd. = 190 tons X 10.5=2,000$ TOTAL=3,943$ 3,943$X1.60 (inflation factor) = 63,000$-TOTAL</td>
</tr>
<tr>
<td>15</td>
<td>30,000$ Lin.Ft. Joint Seal X 0.10 = 3,000$ 3,000$ X 2.76 (inflation factor) = 8,300$</td>
<td>3” overlay: Asphalt 2,400 tons X 10$ = 24,000$ Tack coat 1,200 gal. X 0.46 = 550$ Asphalt cement 145 tons X 85$ = 12,325$ Total = 36,875$ 36,875$ X 2.76 (inflation factor) = 101,800$</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>Seal coat: 3,943 X 4.43 (inflation factor) = 17,500$</td>
</tr>
<tr>
<td>30</td>
<td>Average maintenance of 0.02$/sq.yd./year = 282 X 30 = 8,460$ 8,460$ X 2.76 (inflation factor) = 23,400$</td>
<td>Resurface: 36,875$ X 9.33 (inflation factor) = 344,000$</td>
</tr>
<tr>
<td>TOTALS</td>
<td>143,700$</td>
<td>559,600$</td>
</tr>
</tbody>
</table>
• In 1979, Las Vegas placed 18 acres (18X4050=72,900 m²) of new airport paving construction for a parking ramp for the international arrivals building.

• Original design: 15” (375 mm) thick concrete over 2” asphalt levelling layer over 12” crushed stone base.

• Design revised to 7” SFRC over 2” levelling layer and 12” gravel base.
• **Officials estimated the cost as follows:**
  – FRC: 148.68$/m³ (includes surface finishing, saw cutting and joint filling)
  – Conventional concrete : 78.95$/m³
  – FRC required less than ½ of conventional concrete.
  – Additional cost savings were achieved by using thinner sections of FRC hence less formwork for shaping the edges of conventional concrete.
Conclusions

• There are many factors affecting cost.

• We have covered some of the most important ones.

• However overall it comes down to consideration of the cost of the concrete and other materials required for a job (including on site labor for placing or fabrication if applicable) versus cost of steel fibers taking into account the additional benefits of SFRC.