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# Bendable Concrete – A State Art Review

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***ABSTRACT***
*Bendable concrete is an Engineered Cementitious Composite (ECC)that has high flexural strength and considerable tensile strength compared to conventional concrete. The CO2 emission is relatively less in ECC which contributes to reducing the global warming effects and promotes sustainable practices. Conventional concrete has a straining capacity of 0.1% and it is a brittle material. In contrast, bendable concrete is flexible and fosters elastic properties. Due to the absence of coarse aggregate,the self-weight of the concrete mortifies.Moreover, the reason for the self-healing capacity of bendable concrete is shown.This paper deals with the straining capacity of bendable concrete when added with different fibers in which Recron fibers showfavorable results. Standard specifications of each material in the mix design and experimental test procedures are also discussed.*

***Keywords:*** *ECC, Straining capacity, Self- healing, Recron*

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## I. INTRODUCTION:

Bendable concrete (BC) is one of the widely used special types of concrete. BC can be a good substitute for traditional concrete where heavy reinforcements are avoided as it can bear numerous tensile stresses comparatively. [4,6] It is proven that Engineered Cementitious Composite (ECC) is 50 times more flexible and 40 times lighter than traditional concrete. [18,25] Instead of coarse aggregate, polymeric fibers such as silica fibers, glass fibers, asbestos fibers, polyvinyl alcohol fibers, AR glass fibers, and polyvinylidene fluoride (PVDF) fibers are used for reinforcing ECC which impart flexibility to the concrete. [1,2,13,25] A slick coating (46 nanometers thick) on the surface of the fiber is formed by incorporating very fine silica sand which allows the fibers to slip when the heavy load arrives and fracturing of ECC is prevented. [11,18]The basic constituents of ECC include cement, fine aggregate, and water along with fibers, mineral, and chemical admixtures. The strain capacity of ECC is 3-7% which is greater when compared to traditional concrete at 0.01%. [5,6,24,25] The uniaxial test results revealed that ECC with polyvinyl alcohol fiber had a crack width of less than 153µm and a tensile strain capacity of 1.67%. [18,35] ECC becomes less permeable and gains self-healing properties when cracks are formed. The PVA fibers retained very good tough resistance and mechanical properties while tested in an accelerated alkaline environment. Even if the ECC is overloaded, the crack remains small. The healing process can be accelerated by incorporating fibers into the concrete mix. [18]The results demonstrate that the chlorine diffusivity of ECC is relatively low and depends on the breadth of the crack that has formed. [32,37] The physical properties of cracked and uncracked ECC are mostly similar. The ECC is healed by air upon the moisture present in the atmosphere. To achieve increased electrical conductivity and self-cleaning in ECC Carbon-black and titanium dioxide nanoparticles were added to the mix. [22,23] The Stability of the ECC is superior in seismic areas. [31]Generally, ECC exhibit a tensile strength of 4-6 MPa and is highly ductile. Despite the low fiber content (2%), ECC exhibits good strain-hardening properties in tension. Because of this, ECCs are used in the surface repair of hydraulic structures, bridge decks, and impact and blast-resistant structures. They are also used as retrofitters and dampers for buildings. [35,41] Bridge deck can be constructed without providing expansion joints while using ECC. [33] Various studies concluded that ECC retains durability and its mechanical properties against sulfate attacks, corrosion, and alternate freeze-thaw effects. [46]

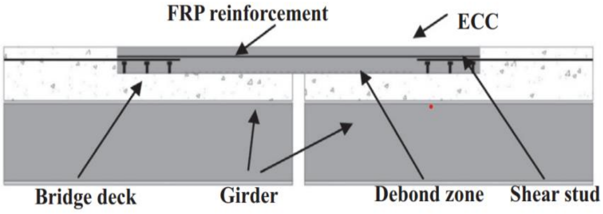



**Fig. 1 Link slab of ECC reinforced with FRP [33]**

## II. MATERIALS USED:

**FIBERS:**

The same outcomes are not observed when different fibers are added to the concrete mix. The fibers can be used for preventing the shrinkage effect in the concrete by minimizing the cracks.Flexural properties of the concrete are altered by using primary reinforcements (fibers).Secondary reinforcements are if the shrinkage and cracks are reduced by the means of bridging the micro cracks.The principal role of fibers in brittle matrix composites is to increase their toughness.Fibers made of glass, plastic, and wire mesh are very weightless when used as reinforcements and so they will be of much use and purpose.[12]Shrinkage due to plastic and drying is controlled and fibers also diminish the bleeding and permeability.Rice husk ash (RHA) is also a replacement for cement due to its demand and it is one of the best additives. In contrast, a midget amount of rising husk is used from the quantity produced. [8]High-performance fiber-reinforced cementitious composites (HPFRCC) are used for testing the tensile strength and ductility to prove they are far better than normally used materials especially to be used in seismic zones for stability. [31]Poly Vinyl Alcohol (PVA) fibers of a length of 12mm and diameter of 39 mm are most used in ECCs. [35]A Linear Variable Differential Transformer (LVDT) was fixed for checking the elongation in the sample on one side. [33]

**A) RECRON 3S:**

The fibers of Recron appear like polyester.As a result of the fiber's polarity, a strong bond forms between the mix and the fiber. [16] By inhibiting shrinkage at the time of hydration, Recron 3s makes the composite composition more robust and durable.Thus, improving the effectiveness and firmness of bendable concrete. [12]

Adding 1 kg of these fibers hinders the micro-cracks due to thawing and freezing in a multi-directional manner. [1] A homogeneous mix is obtained because of the characteristics of the fiber to spread in a uniform manner which in turn reduces the segregation which happens when the mix sets. So, the structure becomes durable when built with such compositions and the plaster becomes inherently stronger. [9] The fiber is cut in a manner so that it has a circular cross-sectional area and the aspect ratio is set to 320 with a length of 2mm and diameter of 0.4mm. [38]

**Fig.2. Recron Fiber[11]**

**B) POLYPROPYLENE FIBER:**

Polypropylene fibers boost up the life span of the structure by reducing the water flow via pores, cover, and capillaries. The diameter of this fiber ranges from 22-35 microns and its length is 19 mm long. [1] The addition of 0.1% PP fiber in PFRC increases the ductility index by 280%, ultimate mid-span deflection by 341%, flexural strength by 16%, Modulus of Elasticity by 42%, impact strength by 163%, but decreases the compressive strength by 38% at 0.2%. [4]The concrete mix was able to take more load and there was a notable increase in the strain capacity when the fiber is added. The tests showed that the strain capacity of the conventional concrete uprose to 140% when 1.5% of the fiber is added. [10]

**C)POLYVINYL ALCOHOL FIBER (PVA):**

To make the ECC structurally strong and crack resistant PVA fibers are added. It forms a homogeneous mix and imparts flexibility in the structure without any compensation in the load-bearing capacity. The cracks are small and most of the time it is not visible to the naked eye because of the uniformly distributed microfibers. [21]It was noted that the compressive strength of the sample with 1% PVA fiber showed a 62% increase and with 1.5% it was a 40% increase. This was tested on the 90th day of the curing process. The ECC contained additives such as very small PVA fibers with a very slick coat and fine silica. [19]On the other hand, the compressive strength decreased by up to 15% when the fiber content was raised by 1.5%.This resulted from a decline in workability as the fiber content was raised, which in turn led to the mix balling up. [10] The strain capacity was higher when the fiber content added was 0.5%.Compared to other fibers PVA has a greater value of modulus of elasticity around 25-40 GPa. 6-10% of the fiber gets elongated and the tensile strength of the fiber is reported to be 880-1600 MPa. [22] The ECC was able to withstand higher temperatures when PVA fibers were added. [24,39]

**Fig. 3 Polypropylene fiber [4]**

When the length of the fiber was 8-12mm and possessed a diameter of 40μm. An intact bond was created by the fiber and cement paste. An interfacial zone composed of Ca(OH)2 surrounds the PVA fiber which appears to be white. This is brought on by the cement slurry's inclusion of Ca+ and OH- ions. As a result of this layer, the fibers and paste are more likely to bond strongly. The fibers which are not coated are highly susceptible to an alkaline environment. [25] PVA-ECC is easy to process by using short lengths such as 8-12mm with a volume less than or equal to 2%. [31] 0.02 percent of PVA fibers are added. [31] The crack developed is less than 100 microns when PVA is used so this fiber is used to provide strength as well as to reduce cracks which makes the structure durable and safe to withstand deflections and chloride penetration which causes corrosion. [36]

**D)STEEL FIBER**

Steel fibers are very strong and around 2% of it is added to the concrete having a volume of 150 $kg/m^3$. These fibers have a diameter of 0.2 mm and extend up to 12mm in length. The fibers are to make the concrete crack resistant as they tend to break easily being a brittle material. [37]The calculated breadth of the failure for steel girders, which are exceptionally strong and the preferred component, was 300 m at 40% of the ultimate load and 750 m at 67% of the ultimate load. [34]

**E) NYLON FIBER**

**Fig. 4 Nylon fiber[28]**

Several factors affect nylon fibers, such as the base polymer type and various additive levels, as well as the conditions during the production and fiber dimensions. Nylon fibers of 12mm in length were used to impart impact resistance and flexural toughness to mix, as well as to increase the load-bearing capacity. [28]

| S. No | Property | Jute |
|---|---|---|
| 1 | Specific gravity | 1.14 |
| 2 | Water absorption | 3.5% |

**Table1: Physical properties of nylon fiber[28]**

It was found that the addition of nylon 66 fibers has imparted a positive outcome in the flexural behavior of ECC samples. [29]

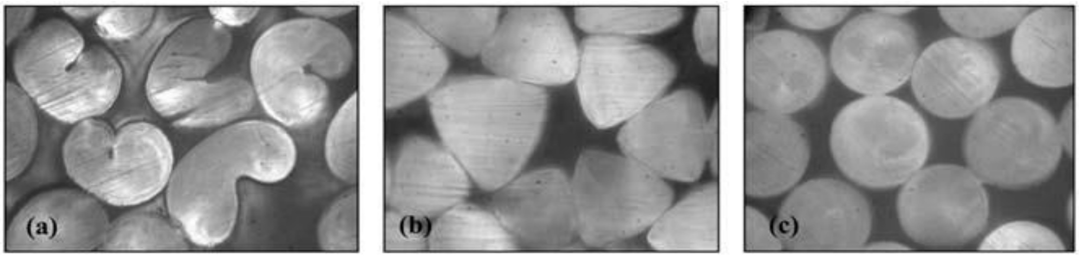



**Fig.5. Images of fibers' cross-sectional shape obtained by optical microscopy (40): (a) acrylic; (b) polypropylene; and (c) nylon 66. [35]**
**(b)**

| **Fiber type** | **Diameter** | **Length** | **Tenacity** | **Elongation** |
|---|---|---|---|---|
| **Acrylic** | **30** | **12** | **2.5** | **48.3** |
| **Polypropylene** | **30** | **12** | **3.9** | **123.3** |
| **Nylon 66** | **30** | **12** | **7.9** | **15.2** |

**Table2: Tensile properties of various Nylon Fibers[35]**

**Testing of fiber:**

50 N load was applied and fibers were set between two clamps which are very small in size. Load–extension curves were derived from these observations. To arrive at a correct result, the data was derived in terms of specific strength which is also known as tenacity. Then in the end the elongation of the fiber was estimated. [35]T-fiber samples showed the maximum load-carrying capacity at 1.2% fiber added is 13.08 MPa. The bending strength results in the decreasing order were: T-fibers > H-fibers > SP-fibers >PVA fibers. [45]

**CEMENT:**

The cement must develop the appropriate strength. Rheological property is important in cement. The cement works better when it is enriched with additives such as silica fume, slag from blast furnaces, and fly ash. [19] Some types of cement give rise to different behavior in terms of strength when they are mixed with these types of supplementary additives.

Ordinary Portland Cement (OPC) having a specific gravity of 3.16 which comes under the category of Grade 53 is utilized in this study. [8,14] The thermal conductivity decreased below 0.1 W m1 K1 when the dense mix was added with the most content of these additives and when lime was added instead of cement. [20]

Cracking in the surface layer is introduced when stresses build up due to shrinkage in Fiber Reinforced Concrete (FRC). Compared to the conventional concrete delamination will not be seen here as the interface shear stress does not deteriorate. [26] In this study, Silica fume SF which is nothing but micro silica being condensed having an activity index of 120% as per ASTM C1240-15 was incorporated, and [25] M of grade 45 was used to make the ECC. [32]

**FINE AGGREGATE:**

Fine aggregates are aggregate that passes through a 4.75mm IS sieve. [2,3,4] River sand belonging to Zone II having a specific gravity of 2.668 of IS 383:1970 is used. [14,38] For sandblasting and polishing, sand is used. The weight ranges from 1,538 to 1,842 kg/m$^3$, based on the composition and size of each grain. The fine aggregate collected from the river Koel's sand bed, which has no organic impurities was used in this experimental program. [22]

**COARSE AGGREGATE:**

Coarse aggregate is defined as the components which get retained in a 4.75mm IS sieve. Polymer fibers were added instead of coarse aggregates as reinforcements. Along with that short Polyvinyl Alcohol fibers were used in place of the coarse aggregates. [10]Aggregate Specification: For this investigation, 20 mm natural coarse aggregates were used and they possessed a 2.72 specific gravity. [5]

**Fig. 6 PET waste [20]**

**SUPERPLASTICIZERS:**

The rheological behavior of the concrete is governed by the use of superplasticizers. The slump value gets increased from 5 cm to 20 cm even without adding water. It is also used as a dispersant to avoid segregation in concrete. The water-cement ratio can be reduced by 15-20% just by mixing superplasticizers. [2,3] 1. Naphthalene-based (Enfiiq Super Plasticizer 400) 2. Polymer-based (Sika Latex Power) contains SNFC. [4] Superplasticizer used is melamine formaldehyde. [8] The superplasticizer used is Conmix SP 1030. Polyethene terephthalate (PET) particles and pulverized Glass Fiber Reinforced Plastic (GFRP) waste were used instead of sand and limestone in the mix. In the measure of increasing the properties of the plaster PET waste particles and wood waste (WW) particles were combined and tested. [20] Here also the water-cement ratio was able to be decreased by adding superplasticizers. [9] In this study, the name of the superplasticizer added is MYK-superplastic 200 and it possesses a specific gravity of 1.148. More workability and higher compressive strength at every stage are observed when polycarboxylate-based superplasticizer is added than the additive SP being based on sulfonated melamine formaldehyde. [19] Superplasticizer used is Conmix SP 1030.

Some crucial properties like density and water tightness get increased when added with superplasticizers in this study. [16] Melamine Formaldehyde Sulfonate is being incorporated as the superplasticizer in this testing. This is used to alter the rheological properties of fresh/conventional concrete. [22]Third-generation superplasticizer Sika ViscoCrete -5930, which has qualities that are comparable to ASTM-C494 Types G and F, was utilized. Superplasticizers have contributed so much in condemning defects like honeycombing in the concrete and have also hugely enhanced the advantageous characteristics a concrete mix should possess. [25]

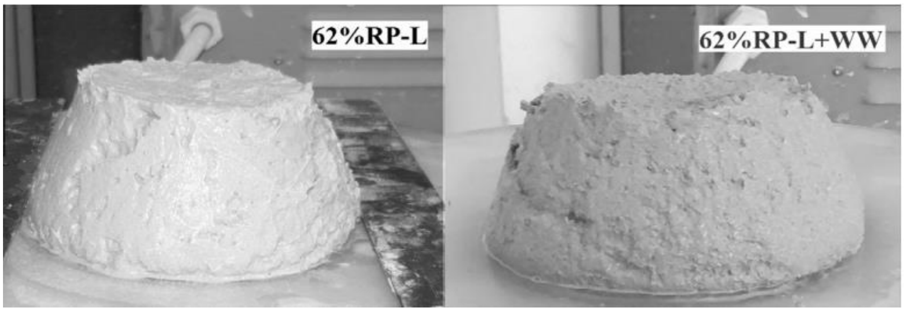



**Fig. 7 Fresh consistency of plasters [20]**

**WATER:**

The concrete is phobic to substances like alkalis, salt, sugar, acids, and organic compounds. They get in the way of concrete only by the means of water. So, water must be free from these substances. Required workability can be achieved by adding High range water reducers (HRWR). [10, 19] Water/cement ratio was found to be significantly less, about 0.2 percent in this study. As a result, capillary pores are not formed as all the water gets used up in the reaction with cement. [37]

**FLY ASH:**

In the power plants where electricity is generated as a by-product of the coal burnt fly ash is obtained. Clay, feldspar, quartz, and shale are the impurities in coal and during combustion, they go out of the chamber mixed with the gases. As they rise along with the gases they cool at a point and get solidified into fly ash. Fly ash is used to diminish heat generation without losing the strength of the concrete and it also enhances the overall strength of the structure. Cement was substituted with fly ash and silica fume along with fiber contents of 0,0.06,0.12,0.18,0.5,1.0% using Naphthalene-based SP. Class C fly ash is used in the making of the specimen. [7] The slump value is maximum at 30% fly ash volume added. It had a cement-sand ratio of 1:0.8. When 40% of fly ash was added the maximum slump value was attained with the same cement-sand ratio but the strength was low when compared. [9]As a result, the compressive and flexural strengths gradually declined as the amount of additive was increased above a certain threshold.A minimum of at least 2 MPa in compression and 1 MPa in bending were noted when hydraulic lime was used in place of cement and virgin raw materials such as fly ash.[20] The Fly ash used was Pozzo Crete dirk 60. In RCC construction usage of fly ash has been of great use in reducing the heat produced. [22] The effect of chloride in concrete is reduced with the usage of fly ash as the chloride ions bind with fly ash. It was observed that the water-cement ratio with a high volume of fly ash resulted in lower chloride penetration than in the conventional mortar mixture. A denser matrix was formed when FA was added as it decreases the pore size, thus, increasing the durability of the structure. The thickness of the transition zone between the fiber and surrounding cement matrix also gets minimized. [32,41]

**SILICA:**

Silica sand is used during the mixing process. [7] It was observed that though silica fume is much finer than OPC it did not require more water. [8] As silica has a high surface area and so it increases the hydration of water which makes the mix harden faster a superplasticizer needs to be added. [37]

**STEEL:**

A new composite, which has a quasi-ductile nature same to steel, classified as "ECC daemon," was implemented in polypropylene fiber manufacturing. ECC behaves like metal rather than steel. [27]Standard concrete fractures with a tensile strain of 0.01% cannot be mounted. It states that presently, the buildings are made stronger by tightening the concrete walls with steel bars so that the cracks are reduced and the structure becomes robust. The steel can be deteriorated to a great extent becoming unrepairable by the salts and water being sprinkled on it. ECC concrete would not require steel reinforcing to hold the width of the crack secure. [27]In contrast to Plain cement concrete beams and SFRC (Steel Fiber Enhanced Beton) composite beams with the same geometry and flexural loading conditions, the ECC beams layered have considerably both load bearing and deforming capability and have strengthened crack width power. [27]

**METAKAOLIN:**

Metakaolin is a pozzolanic material that is created by combining amorphous alumina with silica. It appears to be off-white and it has preferable physical and chemical properties. It is environment friendly as the carbon dioxide emission is low and it has a specific gravity of 2.5. Bleeding of concrete is arrested when using metakaolin and good compressive and flexural strength is observed. [38]

**LIMESTONE:**

SEM-EDS and XRD microstructure analyses reveal that the ECC with LP has more calcite on its surface and throughout its layers than the control ECC.Additionally, it was discovered that control ECC has more C-S-H than ECCL20 in the locations of cracks.The XRD tests revealed monocarboaluminate in the surface and core layers of ECCL20, demonstrating that calcite from limestone and aluminates from fly ash was responsible for the healing process.According to this, the reaction between the fly ash and limestone produced the monocarboaluminate. Moreover, in the lines of cracks, the presence of monocarboaluminate was detected which confirmed that they were a result of the reaction between the calcites and aluminates. When the replacement level of limestone was 5% the results of the tests showed that there was better self-healing as more amount of monocarboaluminate was produced. [53]

**Fig. 8 Limestone powder [53]**

## III. MIX DESIGN:

**Preparing ECC:**

**Nominal Mix Design:**

To prepare an ECC mix, the mix proportions must be calculated. The mix proportions differ for different sizes of the specimen. For Example, (700x150x60 mm) and (700x150x30 mm) mixes require 2% Recron fiber and 30ml superplasticizer for slabs whereas a cube of size (70.6x70.6x70.6 mm) requires only 10msuperplasticizerer.[11]Materials for concrete preparation must be mixed in a certain order to produce a nice, workable mixture.Initially, the mixing drum was filled with all the required materials (such as fly ash, cement, and aggregates) and thoroughly mixed for two to three minutes.The dry materials were followed by the addition of Superplasticizer and Water, which were then combined for the same amount of time as before.The final step involved adding any fiber to improve the flexural characteristic and mixing for an additional three minutes.[17]

**Different Mix Proportions and Mixing:**

There are no standards followed while deciding the composition when fibers are added to the mix. A suitable composition of fibers can be found by the trial-and-error method. [17] To start with the mixing process, the cement, quartz sand, and fly ash were mixed in a dry condition for 5 minutes at 60 rpm. Then, to make the mix consolidate by itself, a high-range water reducer (HRWR) of volume 0.1% of binder was poured while mixing with water into the dry mix and allowed to mix at 120 rpm for 5 minutes. In the end, 2% fiber was added into the mixer and leave for rotating at 60 rpm for a time of 2 minutes. The workable mix was obtained after making it rotate at 60 rpm for 3 minutes. Hobart mixer was used for the entire process.[23] In the mixing process, the superplasticizer was added to obtain the desired workability of the concrete. 2% PVA fiber with 250ml superplasticizer and w/c ratio of 0.4-0.5 is more effective as it improves the flexural property of the mix without compromising the compressive strength. [8,12] When compared to the standard mixing sequence, tensile strain capacity and fiber distribution were increased by the altered sequence of mixing.

| **S. No** | **Content** | **Trail 1** | **Trial 2** | **Trial 3** |
|---|---|---|---|---|
| 1 | w/c | 0.55 | 0.40 | 0.40 |
| 2 | Cement (kg/m3) | 300 | 375 | 375 |
| 3 | Fly ash (%) | 30 | 5 | - |
| 4 | Silica Fume (%) | - | 15 | - |
| 5 | FA (kg/m3) | 893 | 657 | 657 |
| 6 | CA (kg/m3) | 1092 | 1092 | 1092 |
| 7 | SP | Naphthalene | Naphthalene | Polymer |
| | (%) | 0.16 | 0.16 | 0.35 |
| 8 | Fiber content (%) | 0,0.06,0.12,0.18 | 0,0.50,0.10 | 0,0.05,0.10,0.15,0.20 |
| 9 | Mix Ratio | 1:2.98:3.64 | 1:1.75:2.18 | 1:1.75:2.18 |

**Table 3: Trial Mix Proportions [4]**

**Placing, Compaction, and Casting:**

To make the mix consistent and homogenous enough water was added. Hand mixing was done for a period of 10-15 minutes.[9] Before placing the concrete, oil (a mixture of Diesel & Kerosene) must be applied to the mould to make it easier during the stripping of formwork. After placing the ECC, the tamping process was done using a tamping rod to reduce the honeycombing of fresh concrete while placing and vibrators were used to consolidate and level the surface of the concrete.[3] The casting involves, the casting of cubes of size 150mm x 150mm x 150mm, Cylinders of size 300mm x 150mm, and a slab of size 600mm x 200mm x 60mm. [14] 192 specimens were cast with various fly ash proportions and with different volumes of fibers as 2% and 3%.[9]

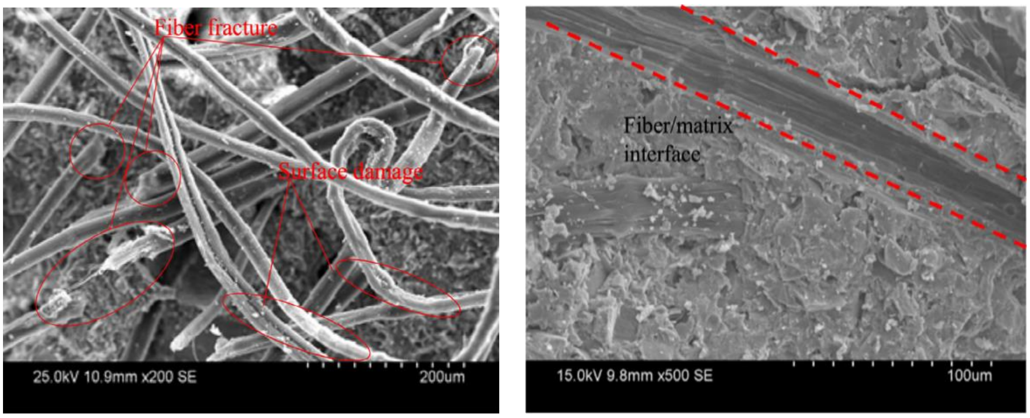
**Curing of Concrete Specimen:**

Ideally, curing of the specimens shouldbe done in a proper way to attain uniform strength. The Specimens after demoulding were dropped in the curing tank under a controlled temperature (23 ± 2 °C) for 28 days. Before testing, the specimens need to be air-dried. [7,8,14] Different curing conditions are air curing, 3% $CO_2$ concentration curing, cyclic wet/dry curing, and water curing.[19]

**SEM Analysis:**

Hitachi S3400 N Scanned electron microscope (SEM) was used to look over the microstructure of the tested specimen. Dumbbell-shaped specimens were taken from the fractured surface of ECC. Using secondary electron imaging, the microstructure and morphology of the samples were observed. [47,50] Three-dimensional semantic data before and after cracking in ECC was obtained by X-ray micro-tomography. The flaws and micro-cracks in ECCs were analyzed using this method. The 3D model was reconstructed by collecting 2D projections at various angles around the rotating axis. A digital detector detects and records the intensity of the X-ray beam and transformed it into computed tomography (CT) numbers.[40] The high bond strength between PE fiber and the matrix is attributed to the large $L_f$/Df ratio of PE fiber. This bond created fractures in the PE fibers. Several fractures were shown in the below picture. [47,50]

**(a) *Fiber fracture and surface damage* [47] (b) *Fiber/matrix interface* [47]**




**(c) Enlarged image showing Healed crack [48]**

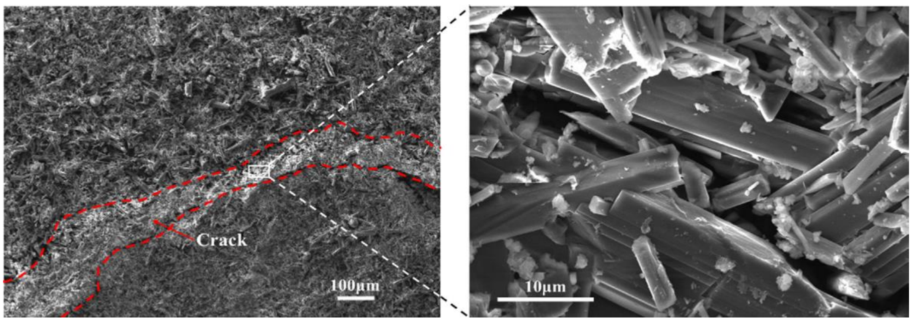



**Fig. 9 SEM Analysis image of FRC**

After the wetting and drying cycles, the crystalline nesquehonite was responsible for patching up the cracks in ECC specimens. This is observed from the experimental results of TGA and XRD. But cracks were not completely healed by nesquehonite. Hence, microstructural morphology and crack interior structure had been analyzed to understand the healing mechanism. In reassembled photos, the crystalline nesquehonite appears to have a lighter grayscale colour since it is less thick than the matrix material.The inside cracks were unaffected, and the ECC's healing process is only taking place on its surface. [48]

**Healing Process:**

In ECC, the healing of the crack was due to mineral dissolution and precipitation. Initially, multiple fine cracks were created by tensile strain but they were bridged by fibers. Dissolution of $Mg^{2+}$, $OH^-$, $CO_3^{2-}$ ions, and $CO_2$ from the air and $Ca^{2+}$ ions from fly ash were facilitated after exposure of the crack to wetting and drying cycles. After the water dried, the ions get crystallized and precipitated. These solid minerals had the highest thermodynamic stability of nesquehonite. The cracks were continuously filled by dissolution and precipitation process. The different stages of self-healing of cracks were illustrated below. [48]

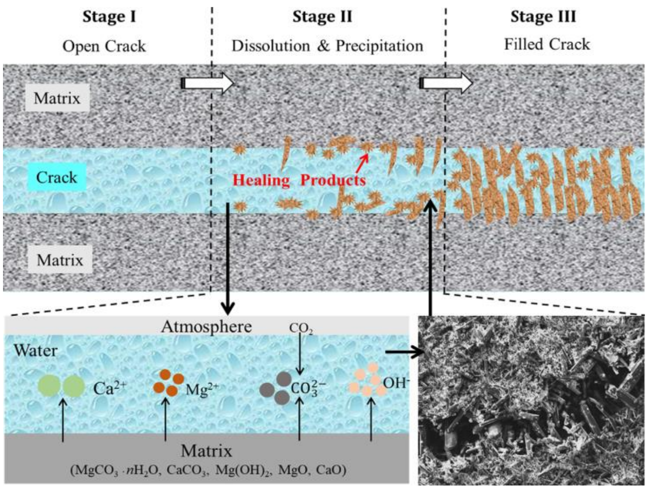



**Fig. 10 Healing process [48]**

**Crack Pattern:**

The permeability of the ECC is impacted by the size and arrangement of the cracks.Under the same tensile strain, Crumb Rubber-ECC (CR-ECC) had lower permeability than Normal-ECC (N-ECC).However, CR-ECC showed more permeability when it was not cracked.This illustrates how the crack width self-control and permeability are related. [51]

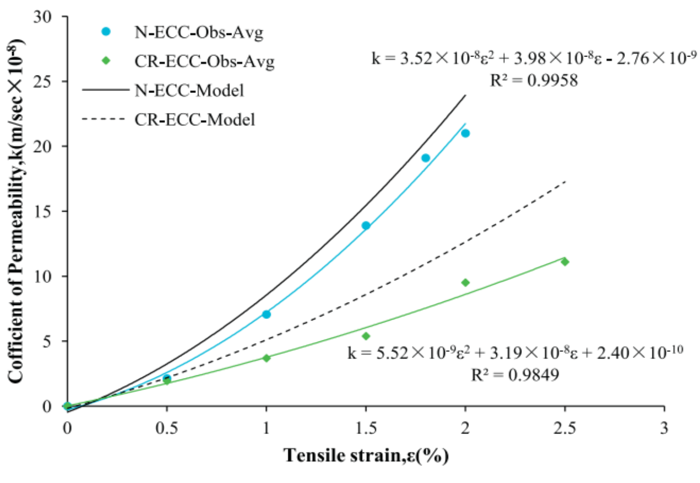



**Fig. 11 Permeability behavior of N-ECC and CR-ECC [51]**

The cracked ECC's behavior could be studied from the experimental data and derived analytical model. This data can be used to predict the performance of ECC in hydraulic structures. The crack pattern of the ECC can be found experimentally from the distributed strain. To accurately simulate the model to real service conditions, crack patterns and self-healing of ECC can be considered. [51]

## IV. TESTING OF CONCRETE:

Grade cubes, prisms, and cylinders of the required dimensions were cast for each nominal mix and these specimens were tested using Universal Testing Machine. The standard size of the cubes, prisms, and cylinders are 15cmx15cmx15cm, 10cmx10cmx50cm, and 15cmx30cm. [6,9]

**Fig. 12 Digital Universal Testing Machine(UTM) [6]**

### COMPRESSION TEST:

At first, the specimen is carefully aligned in Compression Testing Machine (CTM). Then, the load is gradually applied to the smooth face of the specimen till the specimen breaks.[1] Cubes of dimensions 70x70x70 mm and 150x150x150 mm are commonly used for compression tests.[8] Compressive strength is calculated as the cube's total failure load per unit area. Experimental work on FC was carried out on 16 slabs of size 500x110x15mm with fiber contents of 0, 0.5, 1.0, and 1.5% using CM 1:2 shows that the addition of 0.2% polypropylene fiber in PFRC decreases the compressive strength by 38%. [4] For various grades of AR glass fiber concrete mixes, the percentage of compressive strength is 37%. [13]According to test results, compressive strength has a direct proportionality with peak load, flexural strength, and load at first cracking, but a reverse relationship with the index of toughness, deflection, and fracture energy.Compressivestrength is also affected by the specimen dimensions and disclosed weather conditions. The compressive strength can be increased at all stages by incorporating cementitious materials such as fly ash, and silica fume into the paste.[25]

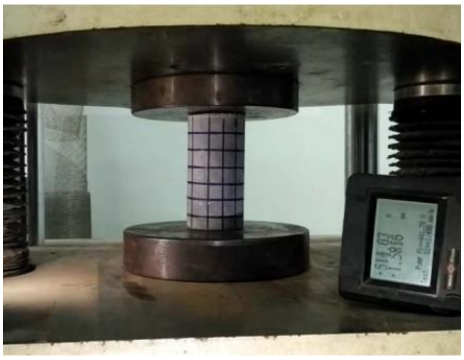


**Fig. 13 Test Setup of Compression Test [10]**

### SPLIT TENSILE TEST:

A cylindrical specimen of 15cm diameter and 30cm length is placed in a Split tensile strength test apparatus and the load is applied till the specimen splits into two parts. It is not a direct test to evaluate the strength of cylindrical samples. This test is conducted at an interval of 7 and 28 days. While applying the load, the fibers in the specimen start to strain harden, and develops micro-cracks. Readings were noted upon slow application of load till there is a split in the sample. [3,5,18] In conventional concrete,the specimen splits into two during the failure, but in bendable concrete, only a crack is developed, showing its ductility.[13]3-5% strain

volume of bendable concrete also accounts for the ductile nature whereas conventional concrete has only 0.01%. [9,22] Split tensile Strength is calculated as,
2P/π*D*L

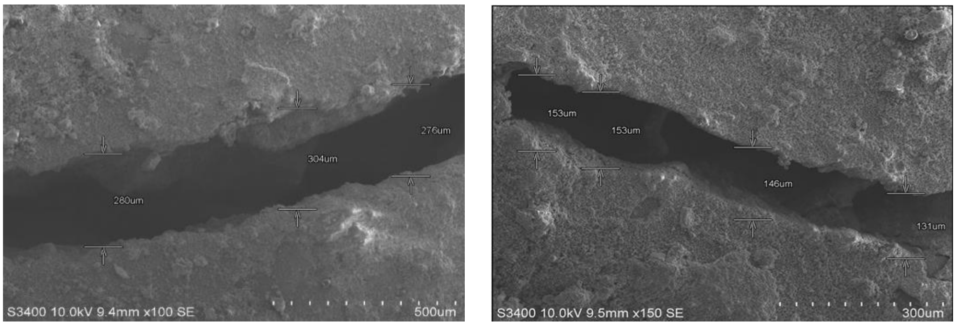



**Fig. 14 Environmental Scanning Electron Microscope (ESEM) image of Microcracks propagation of ECC test specimen of 1% and 2% of PVA fibers subjected to Uniaxial Tensile Test [18]**

**FLEXURAL/ BENDING STRENGTH TEST:**

The test prismsare placed in the bending strength test apparatus in such a manner that the load is applied to the uppermost surface until the failure of the prism.[1] The dimension of the specimens used for testing are 100x100x50 mm and 280x280x75mm. [1,8] Samples were also assembled in the form of sheets to calibrate the flexural performance of ECC composite.[35] The flexural strength of normal concrete is 40% less than ECC.However compressive strength of normal concrete and ECC is approximately equal.[22] The formula for calculating flexural strength is,

Flexural Strength = $3Pl/2bd^2$
Reference from Experimental Study on Flexible Concrete [2,11]

The addition of 1.0% polypropylene fiber in FC increases the Flexural strength by 7.2%. [7] Partial replacement of cement with Recron fiber and fly ash with different percentages of 10% 20% and 30% shows effective results on the flexure.[9] Flexural strength within 28 days is increased by 5.19% for different standards of AR glass fiber concrete mixes.[13] The addition of fibers (i.e., polypropylene and nylon 66) in ECC samples improves the utmost strength of the mixes in comparison with the check specimen. A greater area of deflection hardening zone accompanies this increase in flexural strength. [35] The addition of 0.1% polypropylene fiber in PFRC increases the mid-span deflection by 341%, the Flexural strength by 16%, the ductility index by 280%, the impact strength by 163%, and the modulus of elasticity by 42%.[8] Hence the flexural strength can be increased by the addition of different fibers for the requirement.

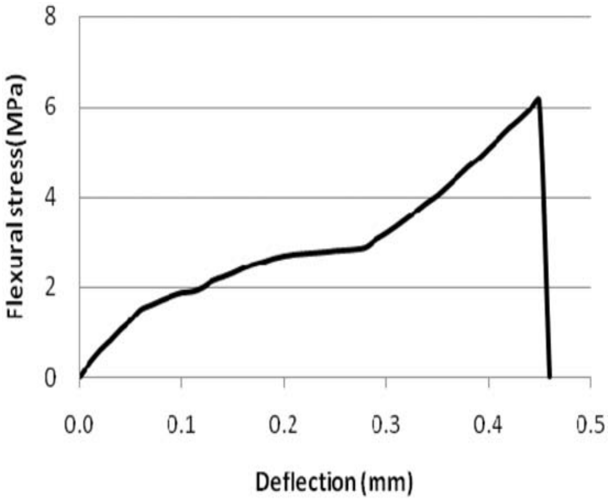



**Fig. 15 Without adding fibers [35]**

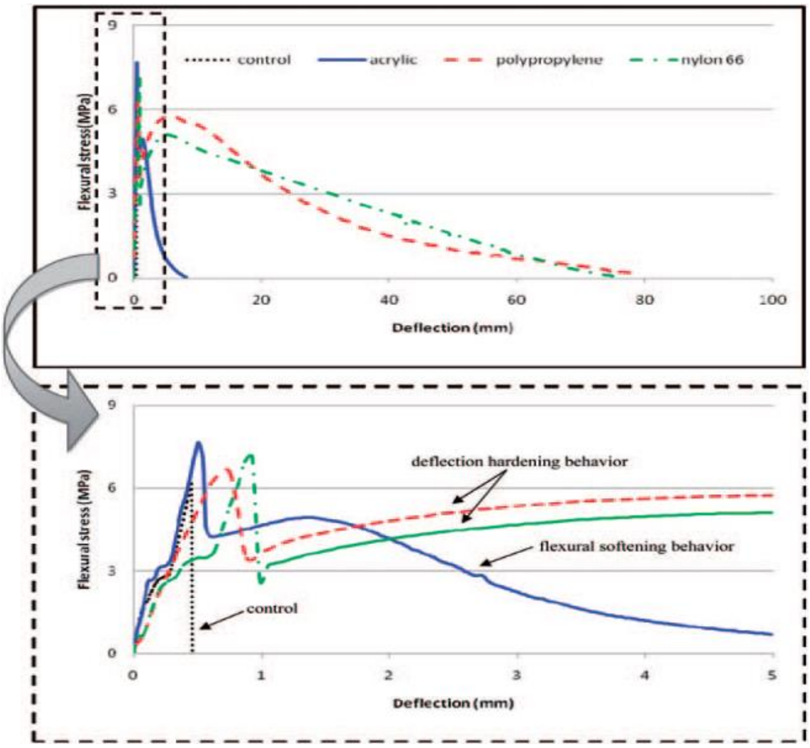



**Fig. 16 Result of the fibers type on the flexural behavior of the ECC samples: (a) stress–deflection curve and (b) magnification of the initial part of stress–deflection curve (dashed line zone) [35]**

**WORKABILITY TEST:**

A slump cone was used to find the workability of the ECC. The slump value varies from 75 mm to 45 mm. post-crack deflection is 14 times at 1.5% but the workability decreases beyond 1.0%. Beyond 1.0% the flexural strength and workability decreases but the mid-span deflection increases. The addition of 1.5% polypropylene fiber in FC increases the post-crack deflection by (14 times). The addition of polypropylene fiber in PFRC and FC decreases workability. The workability reduces when the micro silica percentage is improved.[5]

**THREE-POINT BENDING TEST:**

Based on EN 12 467 standard, a Zwick -1494 machine was used for the three-point bending test after curing [46]. The span length was 200mm and the force was measured using a 1000 kg load cell in this test.
The flexural strength of specimens was calibrated using,

$\sigma = (3Fl)/(2bh^2)$

where σ is the flexural stress, F stands for the maximum flexural load, l for the span, b for the specimen width, and h for the specimen thickness.Load-deflection curves were used to depict the test's results.[35]

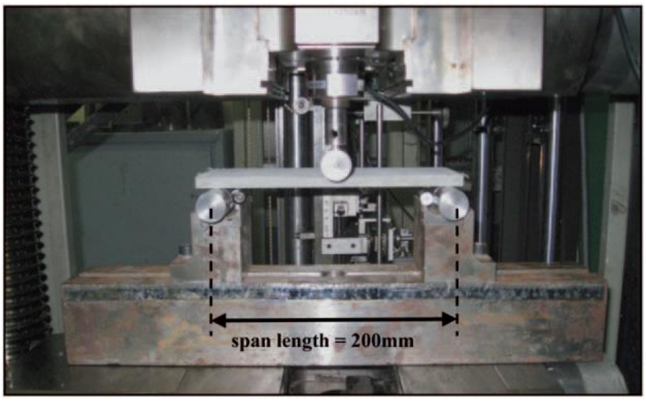



**Fig. 17 Three Point Bending Test [35]**

## V. RESULTS:

**COMPRESSION TEST:**

The below table shows test results after 28 days test,

| Reference | Name of fiber | Load at failure(Kn) | Compressive strength(N/mm²) |
|---|---|---|---|
| 1 | Polypropylene | 567 | 37.66 |
| | Recron 3s | 590 | 39.33 |
| 2 | Polyvinyl Alcohol | 310 | 55.11 |
| 3 | Nylon, Jute | - | 21.34 |
| 8 | RHA | - | 13.6 |
| 14 | AR glass fiber+Recron 3s | 905 | 40.36 |
| 15 | ARGF | 644.2 | 28.67 |
| 16 | Recron 3s | - | 38.27 |
| 18 | PVA 1% | - | 46.22 |
| | PVA 2% | - | 52.71 |
| 23 | PVA 2% | - | 46 ± 2 |
| 24 | 70% LCC + PVA 2% | - | 64.52 ± 6.34 |
| | 80% LCC + PVA 2% | - | 43.58 ± 2.17 |
| 30 | SPECC | - | 53.5 |
| 30 | DRECC | - | 89.2 |
| 37 | RPC | - | 150-200 |
| 38 | Metakaolin | - | 43.12 |

**Table 4: Compression testing results of various fibers**

Improving the water/binder fraction and lowering cement contents witnessesa reduction in strength. The reduction in strength for all restorative ages in the 80% LCC series should be credited to the LCC in contrast with the outcome for the 70% LCC series. Though cement content is less, the aluminate phase in $Al_2O_3.2SiO_2.2H_2O$ (Calcined clay) can react with CaOH(Calcium hydroxide) and $CaCO_3$(Calcium carbonate) forming $Ca_{hn}$(Carbo aluminate hydrates) in the system, which can improve the strength. The reduced strength evolution in 80%LCC is because ofthe lower content of carbohydrates in the system with only 20% cement.[24] As a result, the highest compressive strength is recorded in Reinforced polymer concrete and hence it is the most suitable and popular fiber-reinforced concrete to date.

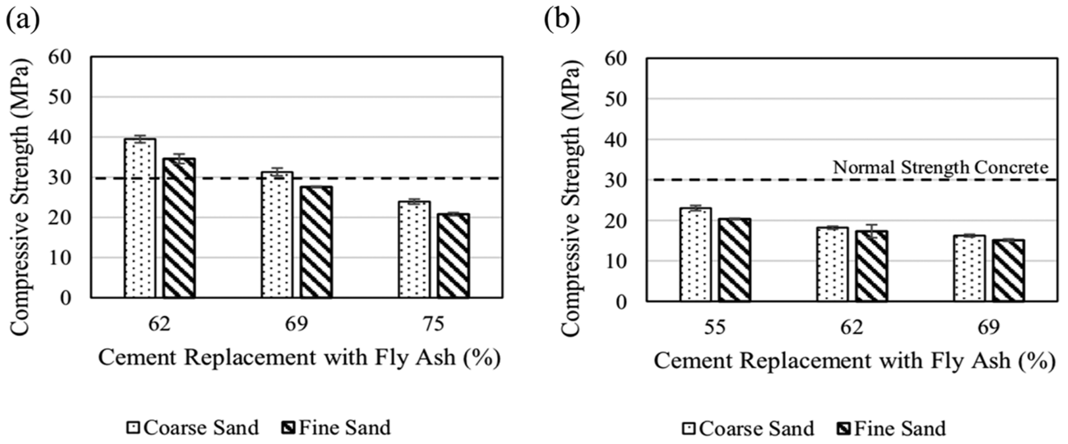



**Fig. 18 Average strength of ECC: (a) regular; (b)crumb rubber [46]**

Compressive strength reduction is an outcome of improving cement replacement with fly ash. Coarse sand exhibited higher compressive strength in contrast with fine sand. Eventually, restoring sand with crumb rubber produced an additional decrease in strength.[46]For 70.7 mm and 100 mm cubes, the average strength values were 121.5 MPa and 112.69 MPa respectively. With the increasing dimension due to the geometric effect, the strength decreased slightly. With a C.o.V of 0.7%, the mean compressive young's modulus was 44.26 GPa.[47] From this, the positives lie on the coarse sand's side and the replacement would be apt for it as compared to fine sand.

**SPLIT TENSILE TEST:**

| Reference | Name of fiber | Load at failure (kN) | Tensile strength(N/mm²) |
|---|---|---|---|
| 1 | Nylon, Jute | - | 4.1 |
| 8 | Palm oil | - | 2.06 |
| 14 | AR glass fiber+Recron 3s | 288 | 4.19 |
| 15 | ARGF | 500 | 6.69 |
| 16 | Recron 3s | - | 5.75 |
| 18 | PVA | - | 6,5.16 |
| 23 | PVA | - | 5.8 ± 0.2 |
| 24 | 70% LCC + PVA 2% | - | 5.19 ± 0.25 |
| | 80% LCC + PVA 2% | - | 4.65 ± 0.11 |
| 30 | SPECC | - | 4.7 |
| 30 | DRECC | - | 6.2 |
| 37 | Steel | - | 2.2 |
| 38 | Metakaolin | - | 3.10 |
| 43 | PVA (with silica sand and HRWRA) | - | 4.71 |

**Table 5: Split tensile strength of FRC**

The strength reduces with improving water/binder ratios and/or improving low cement contents, which is due to a reduction in matrix fracture toughness and a small reduction due to matrix/fiber interfacial activity. The strain volume for the 70%LCC-S40 is slightly (about 10%) greater than those for the 80%LCC-S40. 50% greater strain volume was obtained by having0.2 as the sand/binder ratio which is higher than a greater sand/binder ratio of 0.4. The primary reason for this is because of the low fracture toughness in the latter.[24] Under direct tension, the specific fracture energy of UHP-ECCwas higher than 1500 kJ/m3.[47]

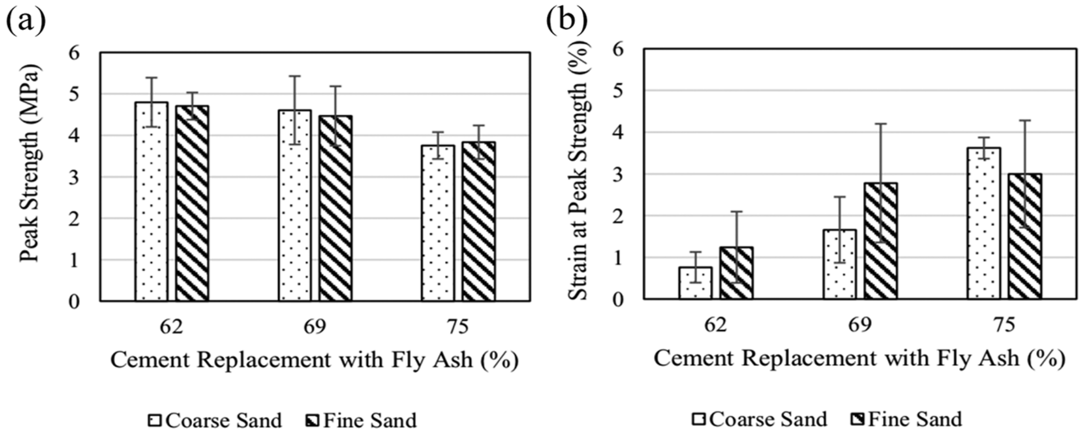



**Fig. 19 Uniaxial tensile test results of regular ECC: (a) peak strength; (b) strain at peak strength [46]**

Bendable concrete contents were highly exposed to strain by the material. The cause isthe strength of composites and ductility. In contrast,escalating the cement replacement with fly ash resulted in a reduction of strength and improvedthe ductility of bendable concrete.[46] So, we get one benefit on consideration with the other as a result when it comes to the tensile strength of the specimens tested.

**FLEXURE TEST:**

| Reference | Name of fiber | Load at failure(kN) | Flexural strength(N/mm²) | Deflection(mm) |
|---|---|---|---|---|
| 1 | Polypropylene | 18 | 13.8 | - |
| | Recron 3s | 20 | 15 | - |
| 2 | Polyvinyl Alcohol | - | 5.56 | - |
| 3 | Nylon, Jute | - | 15.86 | - |
| 7 | PVA | - | 4.62 | - |
| 8 | Palm oil | - | 10.7 | - |
| 14 | AR Glass fiber+Recron 3s | 18 | 15 | - |
| 15 | ARGF | 15 | 5.97 | - |
| 16 | Recron 3s | - | 7.45 | - |
| 35 | Without fiber | - | 6.15 | 0.46 |
| | acrylic | - | 7.64 | 8.18 |
| | polypropylene | - | 6.58 | 78.55 |
| | Nylon 66 | - | 7.20 | 76.64 |

**Table 6: Flexural strength of FRC**

The results of the testing on the bendable concrete link slab are disclosed, together with the suitable deformation results. The ECC matrix deforms together with the reinforcement provided inside because of its higher ductility. Due to the larger load placed on the reinforcement bars in a standard concrete slab, more reinforcement bars are needed. In contrast, the reinforcement experiences less stress in the ECC link slab. This was ascribed to the ECC matrix's ability to withstand stress. So, using the ECC matrix rather than the traditional matrix can lower the number of reinforcing bars needed.[34,35]

**SLUMP TEST:**

It is an empirical test for the measurement of the workability of fresh concrete. The slump test calibrates consistency amidst batches. For various mixes of ECC, the smallest slump was 31mm and the highest slump was 47 mm. As the volume of fibers in the mix increases, we can observe decreasing slump from the results. The mix becomes tough as the volume of fibers increases.

| Replacement of fly ash with cement | Cement/Sand ratio |
|---|---|
| 30% | 1:0.8 |
| 40% | 1:0.8 |

**Table 7: Percentage of replacement**

The apparatus and the procedure of the testwerefollowed according to IS 7320-1974.[22] By adapting super-plasticizers, the small slump flow diameters for ECC mixes can attain 16-20cm, which is identical to normal concrete.[24]

## VI. CONCLUSION:

Although the price of bendable concrete is around 2-3 times greater than the price of regular concrete, the maintenance cost is relatively lower than that of regular concrete. It is inferred that bendable concrete in addition to Recron fiber shows an efficacious result when compared with conventional concrete. In case we add 2% of it to the concrete mix it shows extensive strain hardening of 0.01% compared to the conventional concrete. In contrast, concrete with 20% fiber replacement is more effective as compared to other percentages of replacement. In terms of flexural strength, it is achievable by the reduction of the water-cement ratio in the concrete mix. It can be concluded that the flexural strength of M30 ECC is 100% more than thatof conventional concrete.ECC remains intact by bearing tensile strength of more than 5% as compared he traditional concrete which suffers catastrophic failure when strained. 29-63% of carbon-di-oxide emission can be reduced by using Iron Ore Tailings (IOTs). Hence greener ECC with reduced energy consumption canbe developed. The Compressive strength of M30 ECC increases with an increase in the volume of fiber. The fatigue stress level of ECC is 60-75% which is higher than the SCC fatigue stress level of 45%. PVA fiber in ECC with the volume of 1% and 2% shows 28 days compressive strengths of 46.22 MPa and 52.71 MPa respectively. It also shows 6.00 MPa of direct tensile strength while a 2% volume of fiber is mixed with ECC. The microcrack widths of ECC were analyzed using an Environmental Scanning Electronic Microscope (ESEM) which shows only 153 µm to 131 µm for 2 % of PVA fiber and had a tensile strain of 1.67%. PVA fiber concrete had an excellent strain hardening property as compared to conventional concrete. At 28 days, HVLCC-ECC can give us a tensile strength of 3.24-5.19 MPa with a tensile strain capacity of up to 0.57-1.58%. The sequel of increasing the water/binder ratios is the reduction in tensile strength. In conjunction with increasing LCC constituents, when there is an increase in tensile strain capacity it will result in an increased water/binder ratio. The 28-day compressive strength can reach up to 38.4-64.5 MPa and 33.6-43.6 MPa for ECC with 70% and 80% LCC in order. Despite adding 70-80% of LCC to the matrix of the ECC, early strength was achieved only in 3 days. Nonetheless, the comparison reveals that ECC with fly ash performs much better than ECC with LCC in terms of EE and EC strain capacity. From an economic standpoint, HVLCC-ECC with reasonable mechanical performance would be a good choice because there will be a shortage of fly ash in the future as coal usage decreases. Moreover, the results show the strong rate dependence in PVA-ECC M45 reason being the tensile properties making it safertouseit,especially in the seismic zones.

Ordinary Portland cement mixes have less compressive and tensile strength than Portland limestone cement mixes. This is because of the less clinker found in Portland limestone cement. Bendable concrete can be achieved by adopting Portland limestone cement as it has a very less drying shrinkage value. It has reasonable compressive and flexural results that are not very high or low.Incomparison with IL Cement also, OPC gives a better result in terms of compressive and flexural strengths in the test. It is again the quantity of clinker formation playing a major part in the development of strength at an early stage. In the competition for best bendable behavior, SPECC had the best results with its maximum strain value of 2.6%, which is 20 times the strain at which the failure occurred in PC.

Corrosion can be condemned by reducing the width of the crack in ECC. A crack width lesser than 0.008 inches hasa minimal striking influence on chloride intrusion compared to cracks having a width greater than 0.02 inches. At large inflict deformation level, the number of cracks in ECC increases even though the crack width remains constant. However, the effective diffusion coefficient of the microcracked ECC is reduced when it is introduced to NaCl solution leading to Self-healing of the ECC cracks. It is a positive note that ECC cover has a lower depth of penetration on chloride ions compared to that of conventional concrete cover and when ECC is prepared with acrylic fibers, the maximum flexural strength is achieved. The toughness and deflection of composites in ECC comprising polypropylene and nylon 66 are increased to about 80mm when fibers are appended. The emergence of Ettringite takes place and the damage in ECC is proven to be less than that of normal FRC when Sulphur or chlorine reacts. In a nutshell, the stiffness of ECC specimens preloaded to 1% strain is recovered nearly to 35% after one-quarter year when healed in a natural environment making it the best suited with such desirable properties.

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