Development and Study of Bendable Concrete for Structural Applications

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Abstract: Development of Bendable Concrete using Polyvinyl Alcohol (PVA) fibers is undergoing a number of phases since Last Decade. The Advancement in Concrete Technology has an ample scope in using these fibers for the purpose of increasing the Potency, Fulfillment and Resilience of Concrete which are the three foremost requirements of any High-Strength, High-Performance and High-Durable Concrete. This Paper focuses on Development and Analysis of PVA Fiber Reinforced Concrete or ECC (Engineered Cementitious Composites or Bendable Concrete) in its Fresh and Hardened state with PVA fiber content of Zero Percent to Two Percent by Volume of Concrete with an increment of 0.25 Percent fiber. The significance of micromechanics in the material design is emphasized. The tensile strain-hardening behaviour of ECC is also recognized in this paper. Linear Regression is acclimated to Foretell strength of ECC at the age of 28 days for different percentages of fiber by volume using Microsoft Excel and MAT Lab.

Keywords: ECC, PVA fiber, Master Glenium 8233, Fly Ash, Linear Regression

I. INTRODUCTION

Concrete is the Principal material used in infrastructural development as structural material on Planet Earth. Nearly Twelve Billion Metric Tonnes of Concrete is consumed annually from corner to corner of the world. It was estimated that one kg of Cement production generates almost one kg of CO_2, a major donor for increased temperature in the atmosphere, making the Earth much warmer. Portland Cement, though expensive and energy exhaustive is the most far and wide used element in the production of different Concrete Grades. Regrettably, manufacture of cement itself involves release of huge quantity of CO_2 into the atmosphere. Hence, it is expected either to hunt for a new material or partially replace it by a substitute material. This approach in essence leads to a sustainable construction.

Structural Engineers who have urbanized High-Strength Concrete Bridges, Skyscrapers and Concrete Pavements from bygone few decades have given confidence to build stronger structures. However, when we look back, major failures are due to brittle fracture in tension. Escalating the tensile strength of concrete is the most essential requirement in expanding the material property of concrete for Durable Structures.

Revised Manuscript Received on July 30, 2020.
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II. LITERATURE SURVEY

Concrete is the significant building material used across the globe. In the past, structural engineers have largely relied on concrete to carry mainly compressive loads.

However, in realistic conditions, concrete is moreover subjected to tensile stresses due to loading and environmental effects. The tensile strength of concrete is only ten percent of its compressive strength [1].

The Bendable Concrete (BC) and Conventional Concrete (CC) are alike in their compressive strengths. However, CC has a strain ability of 0.01 percent whereas BC has a strain ability of 3.00 to 5.00 percent. BC is something like a ductile material leading to an ample range of applications. The infrastructure in several countries is not unique and in good quality. Certainly, many countries are under economic crisis. Every single problem in concrete construction makes design engineers to go for unconventional materials. It is something like our body does not require stitches for small cuts and it heals by itself. BC will undergo self healing process like small cuts whenever it experiences micro cracks. It is a fact that concrete behaves well in pure compression. However, many structural elements suffer bending and shearing stresses and perpetually introduce tensile stresses. Cracking due to the least plasticity of concrete and fracture thereafter occurs when enduring damage occurs before the yield stress is reached. This is common in case of dynamic loading, where compressive stress waves create tensile stress waves. High velocity debris can be seen at the free surface and also the use of steel reinforcement is least recognized and spalling is inevitable [2].

The oxidation of steel is the cause of deterioration and reduction in the life span of the concrete structures. Recent study reveals that frequent maintenance of structures calls for "CO_2 Emission", unnecessary consumption of "Invaluable Material Resources" and huge amount of "Energy Consumption". Onset of corrosion is always prevented by good quality concrete. Reduced corrosion induced damage will contribute to the sustainable development [3].

Due to the variation in climate and extreme weather conditions, the durability performance of infrastructure is significantly reducing day by day. Reduction in CO_2 emission of producing cement and a concern towards the Humankind and Environment is utmost important as expressed by Professor Li. This was the motivation behind developing Bendable Concrete as said by Professor Li of University of Michigan. [4]. The Bendable Concrete bends but does not fracture.

The Cementitious Composites exhibit continuous propagation of tiny crack widths due to various loadings and takes care of the healing process. This was documented by Victor Li and Benjamin Wylie [5]. Bendable Concrete exhibits better fracture toughness and is comparable to that of Aluminum Alloy. Under high shear stresses also it remains ductile. The conventional concrete experiences brittle failure and also there will be significant loss of structural integrity. Increased tensile ductility and greater fracture toughness are the uniqueness of Bendable Concrete. [6] Self healing or autogenous healing is the ability of BC to heal itself in presence of $Ca(OH)_2$ and moisture. In this state micro-cracks of BC get sealed by the formation of lime-stone or carbonic salt of Calcium ($CaCO_3$). PVA fibers help in propagation of continuous and tight crack widths which will take care of self healing. Another approach involves embedment of capsules which contain self healing compounds. [7] If resilience and sooner or later sustainability are important, present construction practices and design codes must keep trying an exemplar shift to attain concrete structures so as to have tight cracks or crack-free in preference to high strength. [8] When Calcium Oxide (CaO) is dissolved in water, a solution supersaturated with respect to crystallized calcium hydroxide is quickly formed. Hydrated mature cement paste consists of Calcium Hydroxide (lime) which amounts to be nearly 26 percent of the total hydrated paste volume. Calcium Hydroxide forms a thin layer on the PVA fibers and creates strong bonding within the cement matrix. It looks like reasonable to think that $Ca(OH)_2$ layer plays an important role for developing strong bond strength [9].

John Philip established the term Sorptivity in 1957. The ability of a material to absorb liquid by capillary action is called as Sorptivity. It is the tendency of a material to attract and diffuse water and other liquids by capillarity. Water repellent admixtures play a very important role during the upward movement of water against gravitational force. The developed micro-cracks of Bendable Concrete due to various loading conditions increase the Sorptivity. Many of the water repellent admixtures and especially water soluble silicone based one will inhibit the Sorptivity. Water transport by the action of suction in cracked or un-cracked BC has been found to be least when compared with a sound conventional concrete. [10] A study carried out by Professor Li and his associates revealed the autogenous healing of cracked specimens in highly concentrated solution of chloride. The capillary action is identical both in water environment and chloride environment. Complete recovery was found in their research with respect to tensile strain capacity of Engineered Cementitious Composites. Specimens immersed in 3 percent Sodium Chloride solution after subjected to 1.5 percent tensile strain for 30 days shows better results. [11]

III. METHODOLOGY

The Methodology has been divided in to three phases. The 1st Phase includes the proper selection of right materials and development of the ECC mixes through several trial mixes. 2nd phase covers the study of deformability characteristics in their wet conditions. The 3rd phase highlights the study of hardened properties of developed mixes in the laboratory.

Cement, fly ash and fine aggregates are to be thoroughly mixed in dry conditions until the mixture is completely blended to arrive at uniform color. Almost 75 percent of water and Super-plasticizer are to be added and mixed thoroughly until the concrete appears to be homogeneous. The remaining water and Super-plasticizer are to be supplemented, mixed and then PVA fibers are to be introduced. All the constituents are scrupulously mixed awaiting the desired homogeneity and consistency.

IV. INGREDIENTS OF POLYVINYL ALCOHOL FIBER REINFORCED CONCRETE

BC or ECC be similar to regular conventional concrete and weighs 40 percent less. All ingredients of BC are similar to that of convention concrete except coarse aggregates. Tiny Polyvinyl Alcohol (PVA) fibers of 8 to 12 mm long and diameter about 40 microns are used. The thickness of the fiber is about half the thickness of a human hair. Nanometer-thick surface coating allows them to slide to a certain extent than split under heavy loads. In place of coarse aggregates, it relies on fine sand as coarse aggregates agitate the placement of fibers and devastate the ductility.

A. Cement

53 Grade Ordinary Portland Cement was used. The material properties of the Cement are shown in Table 1.

B. Fine Aggregates

Locally available Sand was used and the physical properties are shown in Table 2.

C. Fly Ash

Fly Ash used was Class F and brought from Raichur Thermal Power Station (RTPS). Some of the Properties of Fly Ash are shown in the table 3.

D. Superplasticizer

High performance MasterGlenium SKY 8233 (Formerly Glenium B233) Superplasticizer derived from Polycarboxylic Ether (PCE) was used. The Performance Test Data is shown in Table 4.

E. Polyvinyl Alcohol Fibers

Ultra-High Performance Fibers were used. Performance Test Data is shown in Table 5

F. Water

Unpolluted Water which is fit for drinking was used.

Table 1. Physical Properties of Cement (Conforming to IS 12269-1987)

Sl. No.	Description of Test	Results
1	Specific Gravity	3.15
2	Fineness of Cement	0.05%
3	Standard Consistency of Cement	32%
4	Initial Setting Time	55 minutes
5	Final Setting Time	360 minutes

Table 2. Physical Properties of Fine Aggregate (Conforming to IS 383-1970)

Sl. No.	Description of Test	Results
1	Shape	Round
2	Fineness of Sand	2.76
	Size	4.75mm down
3	Specific Gravity	2.69
4	Bulking of Sand	27.7%
5	Zone of Sand As per Indian Standards (IS)	III
6	Surface Moisture	Nil
7	Moisture Absorption	0.5%

Table 3. Physical Properties of Fly Ash

Sl. No.	Description of Test	Results
1	Loss on Ignition	2.26 %
2	Bulk Density	2.1163 gm/cc
3	Silica Content	66.06 %
4	Alumina Oxide	0.005 %
5	Calcium Oxide	6.29 %

Table 4. Performance Test Data of Master Glenium SKY 8233

Sl. No.	Description of Test	Results
1	Loss on Ignition	2.26 %
2	Bulk Density	1.1163 gm/cc
3	Silica Content	66.06 %
4	Alumina Oxide	0.005 %
5	Calcium Oxide	6.29 %

Table 5 Performance Test Data of PVA fiber (ASTM confirming to ASTM C1116)

Sl. No.	Parameters	Results
1	Diameter	8 Denier (38 Microns)
2	length	0.375″ (8 mm)
3	Specific Gravity	1.3
4	Tensile Strength	210 ksi (1400 MPa)
5	Flexural Strength	4200 ksi (30 GPa)
6	Melting point	435ºF (225º C)
7	Color	White
8	Water Absorption	<1% by Weight
9	Resistance to Alkali	Excellent
10	Concrete Surface	Not Fuzzy
11	Corrosion Resistance	Excellent

V. EXPERIMENTAL STUDIES ON ECC (BENDABLE CONCRETE)

This includes Mix Design and various tests on ECC in its fresh and hardened state.

A. Material Design Methodology

Making of Cementitious Composites is not so difficult if one knows how to tailor the various ingredients. The scientific and systematic selection of various raw materials and proper mix design methods will result in Engineered Cementitious Composites. In general, the selection of raw materials for making concrete was purely empirical. Now, Micromechanics help in design of Cementitious Composites. Size, shape and amount of sand, the tensile strength and aspect ratio of fibers, surface coating on the fibers, knowledge of material processing, water to cement ratio, amount of plasticizer and behavior of mix in its wet condition and so on will aid in the design of Composites..

Ordinary Portland Cement 53 Grade, Natural river sand (IS Zone III), Polycarboxylate Ether (PCE) based Superplasticizer, Fly Ash (Class F) and Polyvinyl Alcohol fibers (diameter 38 microns, length 8mm and the tensile strength 1400 MPa) were used in the design of concrete mix. The specific or recommended guidelines are not available for the Fiber Reinforced Concrete Mix Design. Hence, the Superlative Mix Proportion specified in the Literature of ECC was used in this study. Various trial mixes were tried to satisfy the workability property of the PVA concrete. High volume fly ash content, low Water to Binder ratio of 0.27 with a Superplasticizer dosage of 0.25 percent of cementitious material and an Aspect ratio of PVA fiber equal to 210 has passed the requirements of deformability characteristics of ECC. These requirements have established a target for the tailoring process of materials.

B. Proportioning of Concrete

Various Mix Proportions were tried keeping the Water to Binder ratio as Constant and varying the dosages of Superplasticizer. The various trial mixes carried out for understanding the fresh property of the concrete are as shown in the Table 6. The Trial Mix4 was found more suitable which satisfies the Characteristic Deformability Factor of the flowable concrete. Besides, the mix was homogeneous and there was no segregation and bleeding. Table 7 shows the Mixture proportion of Bendable Concrete (ECC).

C. Compressive Strength Test

The first and the foremost tests to be conducted on hardened concrete in the laboratory are on its compression strength. It gives an idea about the potency of the mix. The various specimens were subjected to axial compression in a Compression Testing Machine (CTM) of capacity 2000 kN

D. Direct Tensile Strength Test

In the design of concrete structures, only compressive strength is taken into consideration during the analysis and design of various structural elements. However, Tensile strength is also a superlative property of concrete. Non-reinforced concrete structures rely absolutely on the tensile strength. The same is factual for durability characteristic. Fig 1 shows the Tensile Strength Test Specimen.

The Specimens were cured for 28 days and subjected to uniaxial tensile tests with suitable steel grippers in a UTM of capacity 1000 kN and under displacement control of 0.005mm/s to know the strain hardening behavior of the PVA fiber concrete and consequential development of micro cracks. Table 8 represents the Compressive and Indirect Tensile Strengths of PVA fiber Concrete.

E. Permeability Test

Onset of corrosion is possible only in the presence of Moisture, Oxygen, Carbon Dioxide, Sulfur Trioxide and of course Chloride ions. The end product of corrosion is what we call it as “Rust” has the volume almost equal to six times the volume of the original steel. To prevent rusting of steel, we need to have water tight or highly impermeable concrete. If water transport is prevented, corrosion will be arrested and ultimately we can avoid spalling up of the concrete due to bursting pressure of rust from inside.

150mm cubes were casted for the purpose of conducting the tests on permeability. The samples were cured for 28 days and then subjected to a water pressure of 0.5 MPa on a surface of 100 mm diameter at the top of the specimen for a period of 72 hrs. The penetration depth of water is measured by opening the specimen into two halves.

F. Rapid Chloride Penetration Test

The Rapid Chloride Penetration Test (RCPT) is used to evaluate the resistance of a concrete sample to the penetration of chloride ions. The RCPT consists of two parts: To obtain consistent chloride permeability values for a concrete batch, each slice is conditioned to start at the same moisture content. Then the concrete is tested by measuring the charge passed through the slice when one side of the specimen is in contact with a Sodium Chloride (NaCl) solution and the other side is in contact with a Sodium Hydroxide (NaOH) solution. The current is recorded at 30 minutes intervals. The method based on Trapezoidal Rule can be used to calculate the charge passed in Coulombs.

Charge passed = $Q = 900(I_0 + 2\ I_{30} + 2\ I_{60} + \ldots\ldots 2\ I_{300} + 2\ I_{330} + 2\ I_{360})$.

Where,

I_0 = current immediately after voltage is applied in amperes

I_t = current at t min intervals after voltage is applied in amperes.

Table 6. PVA Fiber Reinforced Concrete Trial Mixes

Constituents kg/ m³								
Trial Mix	**Cement**	**Sand**	**Fly Ash**	**SP**	**Water**	**Fiber**	**FA/PC**	**W/B**
Trial Mix1	570	455	684	6.760	350.0	-	1.2	0.28
Trial Mix2	570	445	684	5.016	338.6	-	1.2	0.27
Trial Mix3	570	456	684	4.013	338.6	-	1.2	0.27
Trial Mix4	570	456	684	3.135	338.6	-	1.2	0.27
Trial Mix5	570	449	684	3.135	338.6	-	1.2	0.27
Trial Mix5	570	445	684	3.135	338.6	-	1.2	0.27
Trial Mix7	570	445	684	2.508	338.6	-	1.2	0.27
Trial Mix8	570	445	684	1.254	338.6	-	1.2	0.27
SP: Superplasticizer; FA/PC: Fly Ash to Portland Cement Ratio; W/B: Water to Binder Ratio								

Table 7. Mixture Properties of PVA Concrete

Typical Mix	Cement	Sand	Fly Ash	SP	Water	Fiber	FA/PC	W/B
PVA Concrete (Kg / m³)	570	456	684	3.135	338.6	26	1.2	0.27
FA: Fly Ash, W/B: Water to Binder ratio, FA/PC: Fly Ash to Portland Cement								

Table 8 Strength of PVA Concrete

At 28 Days of Age			
PVA Fiber (%)	**Compressive Strength (MPa)**	**Split Tensile Strength (MPa)**	**Flexural Strength (MPa)**
0	36.45	3.78	4.10
0.25	39.92	3.82	5.04
0.5	46.23	4.61	5.75
0.75	44.51	4.62	5.05
1	46.22	5.46	5.88
1.25	46.52	5.84	6.92
1.5	52.13	6.84	4.77
1.75	47.30	12.70	8.31
2	52.71	8.48	8.72

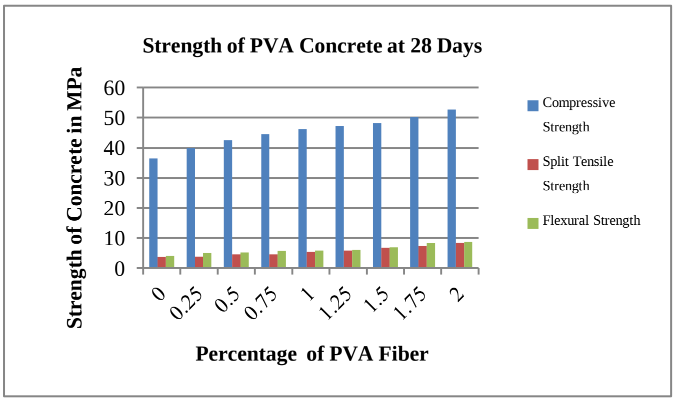

Fig 2. Strength of PVA Fiber Concrete

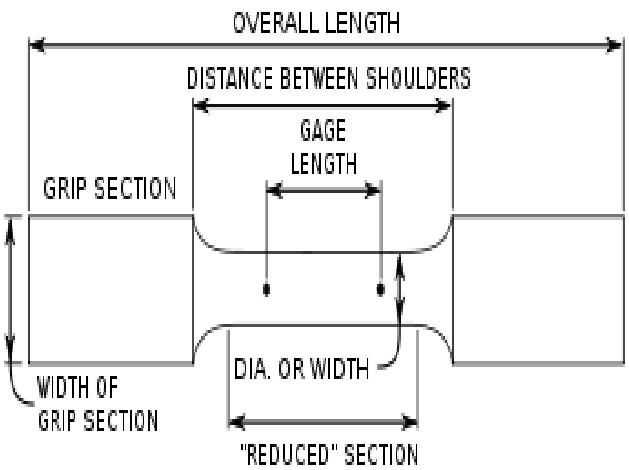

Fig 1. Tensile Strength Test Specimen

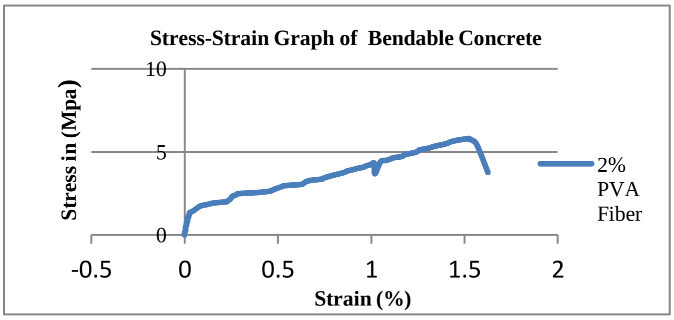

Fig 3. Stress-Strain Curve of PVA fiber Concrete

Fig 4. Permeated water Depth

```
clear all;
close all;
y=38.02;
x=7.27;

for i=0:0.1:2.0;  %for index= initial value, increment,
final value
    y1=x*i+y;

hold on
plot(i,y1,'.'),legend('Y=7.27*x+38.02','Location','Nort
hWest');
hold off
end
```

Image 1. MAT Lab Program

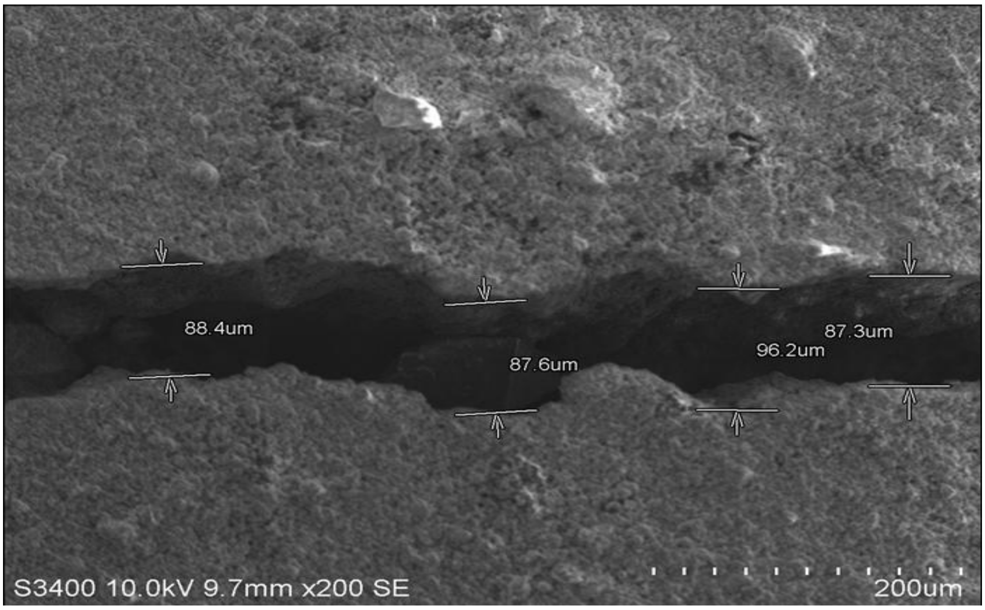

Image 2. Crack Propagation of 2% PVA fiber Concrete at 2% strain (Image captured through ESEM)

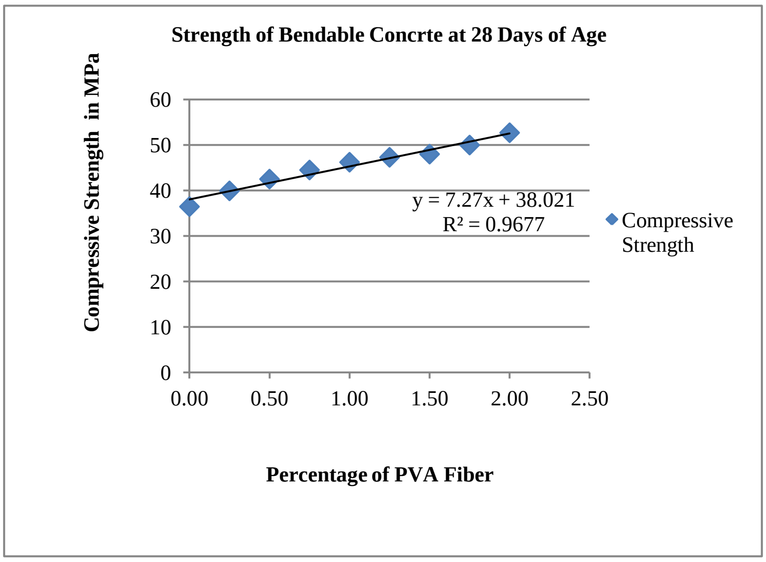

Fig 5. Graph of Least Square and R Square Fitting

Table 9. Least Square Fitting

Sl. No.	X	Y	$X-\bar{X}$	$Y-\bar{Y}$	$(X-\bar{X})^2$	$(X-\bar{X})(Y-\bar{Y})$
1	0.00	36.45	-1	-9.33	1	9.3300
2	0.25	39.92	-0.75	-5.86	0.5625	4.3950
3	0.50	42.51	-0.5	-3.27	0.25	1.6350
4	0.75	44.51	-0.25	-1.27	0.0625	0.3175
5	1.00	46.22	0	0.44	0	0.0000
6	1.25	47.30	0.25	1.52	0.0625	0.3800
7	1.50	48.00	0.5	2.22	0.25	1.1100
8	1.75	50.00	0.75	4.22	0.5625	3.1650
9	2.00	52.71	1	6.93	1	6.9300
Σ	**9**	**407.62**			**3.75**	**27.2625**

Table 10. R Square Fitting

Sl. No.	X	Y	$(Y-\bar{Y})$	$(Y-\bar{Y})^2$	$f_{ckp}=b_0+b_1X$	$f_{ckp}-\bar{Y}$	$(f_{ckp}-\bar{Y})^2$
1	0	36.45	-9.33	87.05	38.02	-7.76	60.22
2	0.25	39.92	-5.86	34.34	39.84	-5.94	35.31
3	0.5	42.51	-3.27	10.69	41.66	-4.13	17.02
4	0.75	44.51	-1.27	1.61	43.47	-2.31	5.32
5	1	46.22	0.44	0.19	45.29	-0.49	0.24
6	1.25	47.30	1.52	2.31	47.11	1.33	1.76
7	1.5	48.00	2.22	4.93	48.93	3.15	9.89
8	1.75	50.00	4.22	17.81	50.74	4.96	24.63
9	2	52.71	6.93	48.02	52.56	6.78	45.97
Σ				206.96			200.36

Where X = Independent Variable (Percentage of PVA fibers);

Y = Compressive Strength as obtained during the Compression Test
= Mean Values of X and

VI. ANALYTICAL MODEL USING MS EXCEL AND MAT LAB

The MS Excel is used to arrive at Linear Equation as y = 7.27x + 38.02 from which the Compressive Strength of any PVA fiber Specimen for the given Percentage of PVA fiber can be Predicted. MAT Lab is also used for the purpose of Predicting the Compressive Strength for any given Percentage of PVA fiber. Table 9 and Table 10 show the MS Excel Data corresponding to Least Square Fitting and R Square Fitting.

A. Equations used in MS Excel

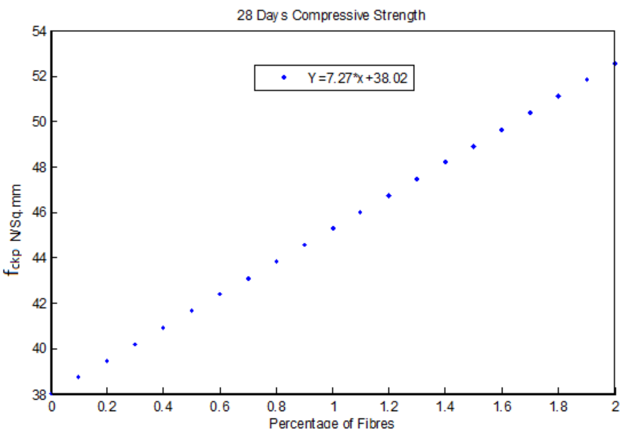

Fig 6. MAT Lab Graph of Predicted Compressive Strength v/s Percentage of PVA fiber

B. MAT Lab Program

A Program in MAT Lab has been developed to predict the Compressive Strength of Bendable Concrete. The MAT Lab Program is shown in Image 1.

VII. RESULTS AND CONCLUSION

The deterioration process of concrete can be considered in two different stages. During the first stage, on account of weathering effects and loading, the voids and tiny cracks developed in the interfacial zone will be gradually interlinked. Later on, several such networks of interlinked cracks will propagate towards the concrete surface and progressively intercepted by the cracks at the surface. This is how fluid transport mechanism takes place into the interior of the concrete. This is the stage where there will not be any noticeable change in the strength but some defensive barricade is being conked out. In other words, the alkaline environment of concrete with p^H 12 to 13 creates an oxide layer (a passive corrosion layer) which prevents steel atoms from dissolving into rust. As long as concrete's inherent protection is not destroyed, the onset of corrosion will not take place.

Corrosion of embedded steel in concrete can be very much reduced by introducing crack-free concrete with low permeability and sufficient concrete cover. Low-permeability concrete can be accomplished by decreasing the ratio of Water to Cementitious materials, use of high volume of fly ash or other pozzolans. This approach increases the concrete resistivity which on the other hand reduces the corrosion rate even after corrosion is initiated. Thus, the strength and durability of concrete can be protected towards sustainable development. The developed Bendable Concrete or ECC shows a very good strain hardening behavior, greater ductility and develops only micro-cracks of the order 60 to 100 μm widths. Bendable Concrete can be established as a near to crack-free concrete thus improving the durability properties of concrete structures. For all structures which call for strength as well as special performance, the Cementitious Composites will have a greater vigor and can be used for variety of applications in the construction industry. Fig.2 represents the Bar Chart which depicts the Compressive Strengths of Bendable Concrete at 28 days.

A Compressive Strength of 52.71 MPa (Mega Pascal) has been attained for a fiber volume of 2 % at 28 days. Fig 3 represents the Stress-Strain curve of Bendable Concrete. A Direct Tensile Strength of 5.80 MPa and a corresponding Strain of 1.525% have been achieved for a fiber volume of 2% at 28 days of age. Fig 4 reveals the depth of water permeated through 2 % Bendable Concrete at 28 days and is only 11.51mm which is less than the minimum cover to be provided in concrete elements. The resistance to water penetration of the developed Bendable Concrete is high and demonstrates the sign of durable concrete.

The charge passed during RCPT test was 1458 Coulombs which indicates a low Chloride Ion Penetrability as per ASTM Standards. Image 2 depicts the Environmental Scanning Electronic Microscope (ESEM) image. The average crack width was found to be 89.88µm when strained to 1.525%. This shows that the PVA Concrete has a very good strain hardening behaviour when compared to Conventional Concrete which has a strain capacity of only 0.01%.

Fig 5 Shows the Graph of Least Square and R Square Fitting in MS Excel. Fig 6 represents the Graph of Predicted Compressive Strength in MAT Lab.

The research work reveals a good strain hardening behaviour and propagation of micro-cracks when specimens were subjected to uniaxial tensile strength test. Also, the paper suggests the importance of Bendable Concrete or ECC for the sustainable development. ECC can be used as an alternative material as far as Strength and Durability are concerned.

ACKNOWLEDGEMENT

The novelist would like to graciously show gratitude to Shatrughna Thimmappa, Columbus, Indiana, USA who has helped us in procuring the indispensable PVA fibers for the Research Work. The Research work was carried out with the assistance from Raichur Thermal Power Station (RTPS), Raichur, India. The authors sincerely extend gratitude to RTPS, Karnataka, India. The author is thankful to Dr. Nagappa U Bhajanthri, Professor of Computer Science, Government Engineering College, Chamarajanagara for his valuable contribution in the MAT Lab Applications.

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