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EXPLORING PVA FIBER REINFORCED BENDABLE CONCRETE: A SUSTAINABLE APPROACH

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ABSTRACT

The paper discusses the development and analysis of PVA Fiber Reinforced Concrete (ECC), also known as Bendable Concrete, using Polyvinyl Alcohol (PVA) fibers. The study focuses on the potential of these fibers in enhancing the strength, performance, and resilience of high-strength concrete. The PVA fiber content ranges from 0 to 2 percent by volume, with increments of 0.25 percent. The paper emphasizes the importance of micromechanics in material design and the recognition of ECC's tensile strain-hardening behavior. Linear Regression is used to predict ECC's strength at 28 days.

Keywords: PVA fiber, Fly ash, Superplaticizer, Self-healing, Sustainable development.

INTRODUCTION

ECC (Engineered Cementitious Composite), a specialized kind of concrete, in the early 1990s. In recent times, numerous nations have augmented their investments in marine engineering due to escalating depletion terrestrial resources. As an illustration, the development of artificial islands is garnering heightened interest in various coastal nations, while research on construction materials is increasingly focused on sea sand and crushed reef aggregate concrete.

The mechanism of ECC is based on the micromechanical interaction of uniformly dispersed structural microfibers and a strong, finely-grained matrix [1] . This designed composite is painstakingly made to provide a concrete that can fracture and bend without losing its strength. Furthermore, because of the evenly distributed microfibers, fissures usually stay tiny and sometimes undetectable. Although the basic components, composition, and ratios of ECC are similar to those of the base mix used in GFRC, they are not the same. Compared to GFRC, ECC blends have less sand, with special attention paid to the gradation of sand in ECC. The fibers, however, are where the two differ most from one another.

ECC is a blend designed to offer flexibility and exceptional bending (flexural) strength, akin to the capabilities of GFRC. Unlike GFRC, which employs significant quantities of large aspect ratio (AR) glass fibers, ECC utilizes relatively modest amounts of smaller synthetic PVA (polyvinyl alcohol) fibers. PVA fibers are unique among fibers used in flatwork because, like AR glass fibers, they have outstanding structural qualities that make them ideal for ECC [2]. Typical fibers like nylon, polypropylene, and cellulose are not strong enough to increase the strength of concrete once it has hardened because they are not elastic enough or have enough tensile strength.

Alkali-resistant (AR) glass fibers are firmly packed and used in large numbers in GFRC; these generally make up 3% of the material for premix GFRC and 5% or more for spray-up applications. GFRC is designed for applications where one side of the casting is ornamental and the other is hidden. It was first developed and optimized for the effective casting of single-sided components. Although it is feasible to wet cast GFRC using solely a flowable backer, a method known as direct casting that eliminates the need for a face coat, the prominent alkali-resistant (AR) glass fibers near the surface may occasionally be apparent. Consequently, the conspicuous fibers in the concrete hinder grinding and polishing. As a result, direct casting is restricted to applications where a surface in its cast state is preferred, and the visibility of large fibers is deemed acceptable [3]. What sets ECC apart from GFRC is the integration of PVA fibers throughout the entirety of the concrete mixture, rather than solely in the backer layer. When appropriately dispersed during mixing, PVA fibers are nearly imperceptible, unlike the GFRC fibers, which must remain in large, highly visible bundles. Due to their transparent nature, short length (only 6-8mm), and significantly smaller diameter compared to a human hair, PVA fibers seamlessly blend into the mixture, rendering them virtually invisible. This streamlined integration simplifies the mixing and casting processes, eliminating the necessity for a distinct face coat. There are serious dangers associated with construction projects due to the limitations of high-strength concrete. Using very ductile materials in seismic parts might improve a structure's seismic performance [4]. For many structural applications, a cement-based material with high ductility is essential, either to reduce the brittleness of concrete or from an earthquake standpoint. In accordance with these specifications, high-ductility cementitious materials are included into engineered cementitious composites (ECC), which are crucial for a variety of structural applications.

ECC can be tailored to be rigid and suitable for hand-packing, or it can be adjusted to be fluid and vibrated. Casting becomes quicker and more efficient, as molds can be filled in a single continuous pour rather than in separate layers. This adaptability renders ECC a practical option for both precast and cast-in-place applications. However, the complexity of ECC makes it impractical to define a mix recipe from scratch. (GFRC, on the other hand, is a simple mixture that is simple to make from scratch.) Because of this, The Concrete Countertop Institute advises against using a homemade ECC mix calculator and instead recommends buying a preblended mix, like the Buddy Rhodes ECC Blended Mix product. Analyzing the mechanical properties of coral aggregate showed that coral particles are very porous, which makes them brittle under shear and compression [5]. They also show significant compressibility. This feature may be the main cause of coral concrete's ductility, which causes it to behave mechanically quite differently from regular aggregate concrete, lightweight aggregate concrete, and recycled aggregate concrete. In order for coral concrete to better meet the ductility criteria of engineering constructions, more study is necessary to improve its ductility. Numerous academics have studied fiber-reinforced concrete in recent years. The basic mechanical characteristics of coral concrete mixed with sisal, carbon, and polypropylene fibers, respectively, were studied. Results show that adding fibers significantly improved coral concrete's mechanical properties. Because of the peculiarities of the sea environment, concrete buildings' longevity often vary greatly based on the kinds of fibers employed. Since coral concrete is a unique construction material intended for use in maritime situations, fibers must have the ability to both increase strength and resilience and display resistance to weathering and corrosion. Therefore, in contrast to other fibers, polyvinyl alcohol (PVA) fiber—which is renowned for its great performance and affordability—might be a better choice. In offshore islands and reefs where traditional construction materials are scarce, the issue of rising costs is both unavoidable and unacceptable. Thankfully, many of these off-shore islands and reefs are abundant in coral resources [3,5]. Thus, devising a novel type of concrete that optimally utilizes these coral resources emerges as a viable strategy for engineering construction in off-shore islands and reefs. Because coarse aggregates affect the ductility of cementitious composites, ECC steers clear of using them. Having a large number of distinct polymeric fibers, ECC is very ductile. The ductility of ECC is attributed to a number of reasons, including as the fibers' ability to slip-harden inside the composite and the meticulous selection of materials and manufacturing techniques. By integrating and interacting with the characteristics of the fiber and matrix, ECC developed from FRC. Optimizing the materials used is the goal of combining the matrix and interface in ECC. Consequently, the failure mode of the composite changes from brittle to ductile. Therefore, fiber function in ECC behavior is quite important. Even though ECC started off as a subtype of HPFRC over thirty years ago , its exceptional ductility , which surpasses that of ordinary cementitious composites, has drawn the interest of scientists. This composite was created to have strain capacities between 3 and 5% and a strain-hardening behavior similar to steel by following the rules of micromechanical design. But from the early 1900s, there has been an increase in the use of fibers in concrete applications to counteract the material's inherent fragility. Fibers added to concrete increase its strength and reduce the likelihood of cracks forming. The effect of fibers on concrete performance has been the subject of several investigations. Moreover, fibers in the mix improve the concrete's ability to withstand punching and shear stresses, which helps to restore post-cracking strength losses. Apart from these benefits, the sole disadvantage of having fiber reinforcement in the concrete matrix is that it may reduce the flowability of the concrete, however this can usually be compensated for by adding admixtures [6,7].

Research and application of coral concrete began in the United States as early as the 1950s. Dempsey [1] and Narver [2] outlined the structural specifications for coral concrete and assessed buildings constructed with this material. Coral concrete was employed in the construction of airports and roads on islands like Midway, Wake, and Bikini, with some of these structures still in operation [6]. Coral concrete structures were first examined in 1974 by Howdyshell and Yuan, who used coral aggregate instead of coarse aggregate for concrete preparation. In 2015, Yuan developed high-performance coral concrete with up to 60 MPa strength. Numerous studies have been conducted on mix proportions, strength, and durability of coral concrete [7]. However, there is limited research on the constitutive relationship of fiber-reinforced coral concrete, which is crucial for operational capacity in concrete engineering structures. Current research findings are insufficient for detailed engineering applications or routine-based designs, requiring further research [7].

Coral concrete, a unique marine building material, requires specific fibers to enhance its durability due to its unique characteristics, including weather and corrosion resistance, making it a crucial choice for marine structures. Hence, when considering different fiber options, polyvinyl alcohol (PVA) fiber, known for its cost-effectiveness and exceptional performance, may present a superior alternative. The newly introduced intelligent construction material, referred to as Bendable concrete or alternatively as Flexible concrete as shown in Fig.1.

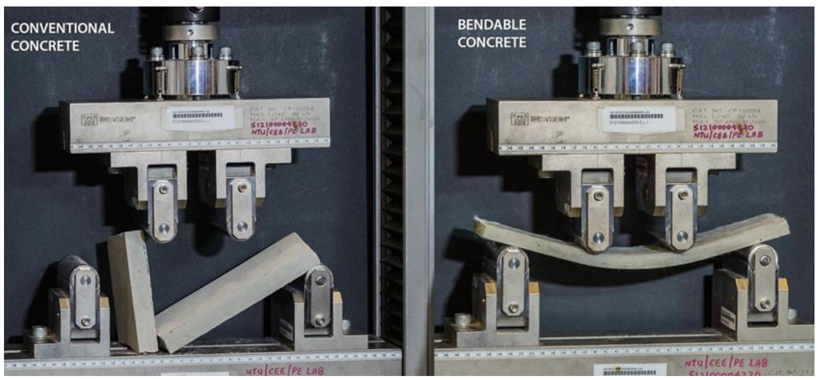

Figure.1. Shows the Conventional Concrete and Bendable Concrete.

The construction built with flexible concrete can withstand higher tensile stresses, preventing collapse from earthquake-induced vibrations. In Japan, a 60-floor building currently under construction utilizes this type of concrete as shown in fig.2.

Figure.2. Shows the flexible Bendable Concrete structure.

Flexible concrete has a flexural strength of 10-15 MPa and a compressive strength of up to 70 MPa. It also has a self-healing property, where cement particles react with rainwater to form complex products that fill microcracks within the concrete. Additionally, flexible concrete has demonstrated a lighter weight and 500 times more flexibility than regular concrete. With an ultimate tensile strain capacity of 3 to 5%, it surpasses conventional concrete by 300 times in strain capacity.

LITERATURE

The primary construction material for structure advancement is concrete, which is consumed in around 12 billion metric tons global each year. However, practically the even amount of CO_2 is emitted throughout the production of one kilogram of cement, which impacts to universal warming. Portland cement is even the extremely often used factor in the invention of concrete, although its high cost and energy use. Cement production produces carbon dioxide into the environment, imposing the use of partially or entirely replaced resources. This assists the use of environmental building techniques. However, failures are frequently caused by brittle cracks under strain. Improving the tensile strength of concrete is essential for long-lasting constructions because structural engineers utilize it as a vital worldwide building material for compressive stresses. It can endure tensile forces from a range of loads and conservational considerations even though its tensile strength is only around 10% of its compressive strength [8,9]. The compressive strengths of common concrete (CC) and bendable concrete (BC) are similar. However, BC has an amazing strain capability varying from 3.00 to 5.00 percentage, while CC can only accept strains of 0.01 percent. Due to its ductility, BC has a obvious range of viable uses. Several nations have low-quality, homogenous infrastructure, which is commonly made terrible by economic declines. Each barrier in the method of building concrete forces design engineers to research non-traditional materials, much to how our bodies certainly mend little wounds that don't involve sutures. It is expected that Bendable Concrete (BC) would experience a self-healing process, like how human skin repairs minor injuries while it encounters tiny fractures. While concrete performs intimately in pure compression, several structural elements experience shearing, bending, and tensile stresses as a conclusion. Concrete's low plasticity is a familiar reason of cracking, which can occur even before the yield stress. Dynamic loading causes compressive stress waves to generate tensile stress waves, exacerbated by high-velocity debris and under-recognition of steel reinforcement, leading to unavoidable spalling due to the underrecognition of reinforcement [10,11].

The corrosion of steel is responsible for the deterioration and shortened lifespan of concrete structures. A recent study indicates that regular maintenance of these structures leads to increased "CO_2 emissions," unnecessary depletion of "valuable material resources," and significant "energy consumption." Employing high-quality concrete consistently helps prevent the onset of corrosion. Minimizing damage from corrosion will further promote sustainable development. The durability of infrastructure is steadily declining due to fluctuations in climate and extreme weather conditions. Professor Li emphasizes the critical importance of reducing CO_2 emissions from cement production and expressing concern for both humanity and the environment. This concern was the driving force behind the development of Bendable Concrete, according to Professor Li from the University of Michigan. Bendable Concrete has the remarkable characteristic of bending without fracturing [12,13].

The documented that Cementitious Composites demonstrate the continuous propagation of minute crack widths under various loadings, while also facilitating the healing process. Bendable Concrete demonstrates superior fracture toughness, akin to that of Aluminum Alloy, and maintains ductility even under high shear stresses [14]. Bendable Concrete offers enhanced tensile ductility and fracture toughness, and self-healing in the presence of calcium (OH)2 and moisture. It has more tensile strength and self-healing properties than regular concrete. Construction techniques and design guidelines should move toward concrete buildings that favor narrow cracks or are crack-free in order to promote durability and sustainability. When calcium oxide (CaO) is dissolved in water, it produces a supersaturated solution, with calcium hydroxide making up around 26% of the volume of the hydrated paste [15, 16]. The Calcium Hydroxide layer on PVA fibers forms a thin coating, promoting strong bonding within the cement matrix. This layer is crucial for the development of strong bond strength. Sorptivity, coined by John Philip in 1957, refers to a material's ability to absorb liquid through capillary action. Water-repellent admixtures counteract water movement against gravitational force. Micro-cracks in Bendable Concrete can increase Sorptivity under different loading conditions [17-19].

However, several water repellent admixtures, particularly those based on water-soluble silicone, effectively mitigate Sorptivity. When examining water transport facilitated by suction in either cracked or uncracked Bendable Concrete (BC), it has been observed to be significantly lower compared to intact conventional concrete. A study on cracked specimens, revealing autogenous healing in a concentrated chloride solution. They found consistent capillary action in both water and chloride environments. Engineered Cementitious Composites showed complete recovery in tensile strain capacity, with specimens immersed in a 3% Sodium Chloride solution showing improved results after 30 days of strain.

APPROACH

There are three distinct steps to the technique. First, the right ingredients must be carefully chosen, and ECC mixtures must be created by several trial blends. Examining these blends' deformability properties in a wet environment is the focus of the second part. In a laboratory environment, the third phase focuses on examining the created mixtures' toughened characteristics. In dry circumstances, mix fly ash, cement, and fine aggregates until they are homogenous. After adding the super-plasticizer and 75% water, add the PVA fibers. Mix until the right consistency is reached. Although they closely resemble conventional concrete, bendable concrete (BC) or engineered cementitious composites (ECC) are around 40% lighter than regular concrete. BC, a kind of concrete, is made of small Polyvinyl Alcohol (PVA) fibers that are 40 microns in diameter and 8 to 12 mm in length. These fibers have a thickness that is half that of human hair. These fibers may glide under large weights because of their nanometer-thick surface layer. To maintain ductility and avoid upsetting the positioning of the fibers, fine sand is utilized in place of coarse aggregates. The physical properties of Cement and PVA fiber performance test data as listed in Table 1 & 2.

Table.1. Properties of Cement.

S No.	Testing Description	Results
1	Fineness of Cement	0.07%
2	Initial Set Time	58 Min
3	Final Set Time	352 Min
4	Specific Gravity	3.17
5	Standard Consistency of Cement	30%

Table.2. PVA Fiber Test Data

S No.	Testing Description	Results
1	Water Absorption	<1% by wt.
2	colour	white
3	Resistance to Alkali	Excellent
4	Resistance to corrosion	Excellent
5	Surface Concrete	Not Fuzzy
6	Diameter	38 Microns
7	Length	8 mm
8	Specific Gravity	1.3
9	Flexural Strength	4200 ksi
10	Tensile Strength	210 ksi
11	Melting Point	435^0 F

Experimental Observation of Bendable Concrete

Producing Cementitious Composites is relatively straightforward with the appropriate understanding of how to customize the different components. Engineered Cementitious Composites can be achieved through scientific selection of raw materials and proper mix design techniques. Micromechanics has significantly improved the design of cementitious composites, considering factors like sand size, shape, tensile strength, fiber aspect ratio, surface coating, material processing, water-to-cement ratio, plasticizer amount, and wet mix behavior, all of which contribute to the composite's performance. Ordinary Portland Cement 53 Grade, natural river sand, fly ash (Class F), polyvinyl alcohol fibers, and a superplasticizer based on polycarboxylate ether (PCE) were all employed in the concrete mix design for Engineered Cementitious Composites (ECC). In order to satisfy PVA concrete workability criteria, the mix proportions were optimized. High volume fly ash concentration, low water to binder ratio, 0.25 percent superplasticizer dose, and 210 PVA fiber aspect ratio all satisfied the deformability requirements.

RESULTS AND DISCUSSIONS

Concrete deterioration may be divided into two separate stages. During the initial stage, loads and surviving initiate small fractures and spaces to develop in the interfacial zone, which ultimately unite. Then, many groups of linked fractures initiate to form and spread in the target of the concrete's surface, progressively coming into contact with surface cracks. This demonstrates the inner fluid transport mechanism of the concrete. Accordingly, this safeguards the strength and longevity of concrete, paying to sustainable development. Bendable Concrete is a type of engineered concrete that has superb strain hardening, ductility, and micro-cracks. It is practically crack-free, developing the durability of concrete structures. Cementitious Composites, which are proposed for strength and elite performance, are suitable for various construction applications. Figure 3 shows the cracks in concrete containing 2% PVA fibers at a strain of 2% after 28 days.

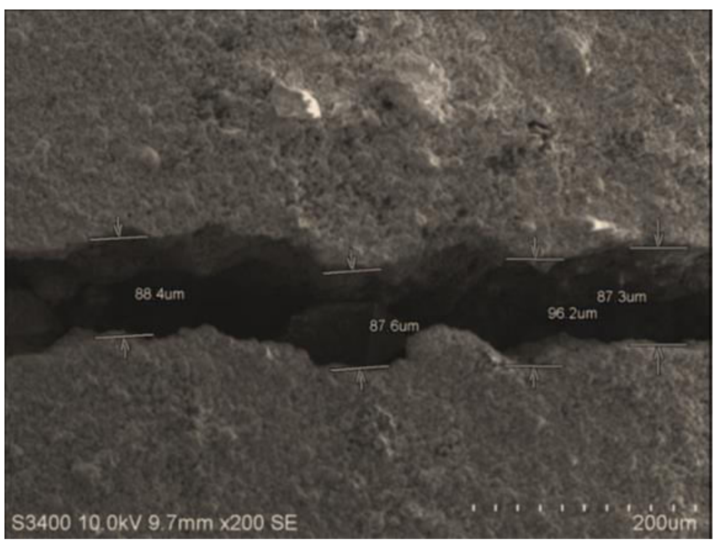

Figure.3. Depicts the propagation of cracks in concrete containing 2% PVA fibers at a strain of 2%.

With a fiber volume of 2%, a compressive strength of 52.71 MPa (Mega Pascal) was attained after 28 days. The Stress-Strain curve for bendable concrete is shown in Figure 4.

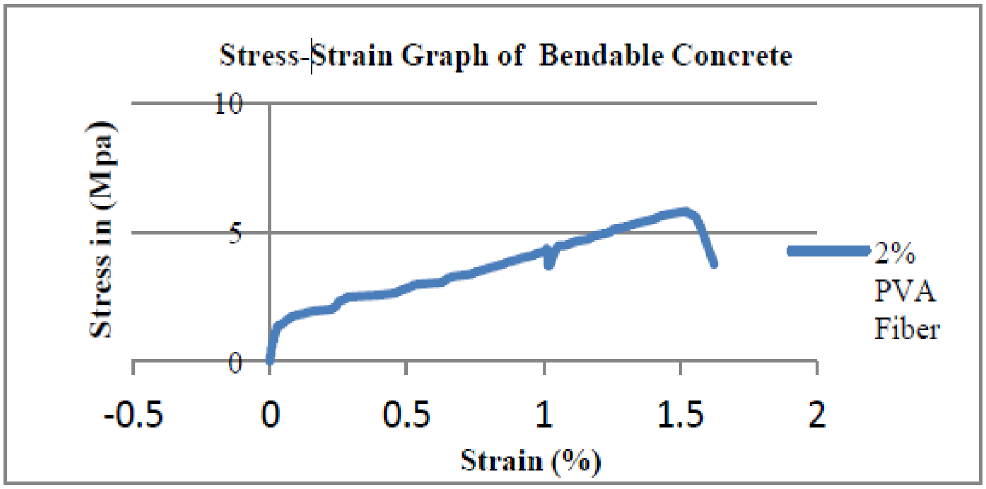

Figure.4. PVA fiber Concrete stress vs strain curve.

At 28 days, 2% Bendable Concrete with a fiber volume of 2% achieved a Direct Tensile Strength of 5.80 MPa and a Strain of 1.525%. Figure 5 illustrates the concrete's water permeation depth, 11.51mm, exceeded the minimum cover required in concrete elements, indicating its durability and high resistance to water penetration.

Figure.5. Water Depth (Permeated).

The RCPT test recorded a 1458 Coulombs charge, indicating low Chloride Ion Penetrability. The ESEM image showed an average crack width of 89.88µm when strained to 1.525%, indicating PVA Concrete's excellent strain hardening behavior, surpassing Conventional Concrete's 0.01% strain capacity.

Two graphs are shown in Figure 6(a & b) of the text: one shows predicted compressive strength in MAT Lab and the other shows least squares and R square fitting in MS Excel.

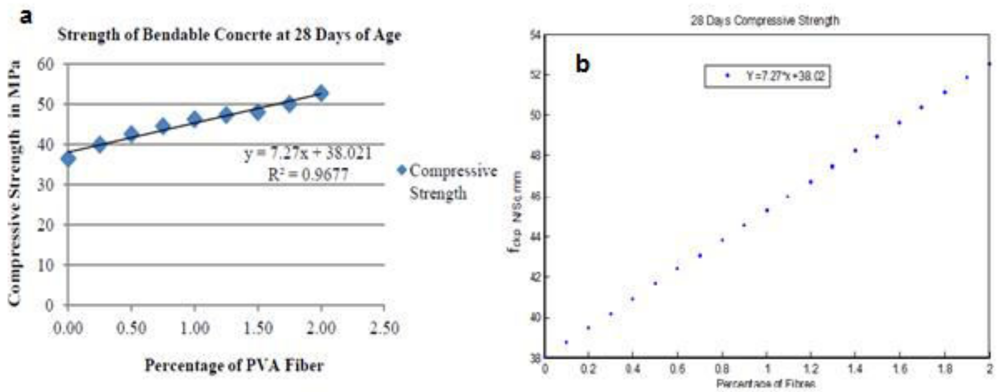

Figure.6. Shows (a) MS excel graph of Compressive Strength vs % of PVA fiber , (b) MAT Lab of Compressive Strength vs % of PVA fiber.

The study demonstrates favorable strain hardening behavior and the propagation of micro-cracks observed during uniaxial tensile strength tests on the specimens. The paper emphasizes the importance of Bendable Concrete (ECC) in promoting sustainable development, as it offers a strong and durable alternative material.

CONCLUSIONS

This work explores the design and testing of PVA Fiber Reinforced Concrete, also referred to as Bendable Concrete or Engineered Cementitious Composites (ECC). The primary focus of the study is the properties of ECC in both its fresh and hardened stages. The PVA fiber content of the concrete was raised by the researchers in increments of 0.25 percent, from 0% to 2% by volume. The research emphasizes the importance of micromechanics in material design and the tensile strain-hardening behavior of ECC. Programs such as MAT Lab and Microsoft Excel were used to estimate the intensity of ECC after 28 days for different percentages of PVA fiber by volume using linear regression approaches.

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