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FRACTURE BEHAVIOR OF ENGINEERED CEMENTITIOUS COMPOSITES CONCRETE UNDER CENTER POINT BENDING LOAD

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Abstract

Fracture behavior is an important issue to consider when analysing and designing important concrete structures. Fracture behavior is dependent on the characteristics and materials percentage in concrete. Thus, due to the application of polyvinyl alcohol fiber, this type of concrete's structure and fracture behavior will differ from normal concrete. This investigation aims to determine some mechanical properties, in addition to the fracture parameters corresponding to low and medium compressive resistance of engineering cementitious composite concrete reinforcing by fiber for notched and un-notched beams, using size effect model techniques in contrast to conventional concrete. The outcomes illustrate an increment in modulus of rupture; both fracture energy and fracture toughness, which were incremented. At the same time, the nominal stress reduction of the notched-beam is superior to un-notched beam. Five mixes for each strength grade were cast to test fresh and hardened properties; the optimum mixture that gave the higher modulus of rupture was chosen for fracture parameters investigations. Two engineering cementitious concrete mixtures containing 1.5% and 2% polyvinyl fiber for grades M25 and M65, respectively, obtained higher modulus of rupture. Geometrically, three (75×75×400) mm, (75×150×800) mm, and (75×200×1200) mm notched-beams were investigated by applying one central point load for testing their fracture toughness, fracture energy, and characteristics length, also the influence of tensile ductility of engineering cementitious concrete. The denser interfacial transition zone of engineering cementitious concrete had the highest fracture toughness and a ductile behavior of mode of failure with a flatter fracture plane than conventional concrete. The higher fracture toughness value was observed on (M25-BC3) and (M65-BC2). Outcomes indicate that conventional concrete exhibited greater sensitivity to size effect parameter due to its poorer tensile ductility than concrete incorporating polyvinyl alcohol fiber.

Keywords:

Polyvinyl Alcohol;
Fiber;
Engineering;
Cementitious;
Composites;
Fracture Parameters;
Compressive;
Resistance;
Size Effect.

1 Introduction

Traditional cementitious composite concrete is a frequently utilized substance in construction. It demonstrates sufficient capacity for resisting compression force at a reasonable price. Still, it has limited ability to withstand tension, a significant density and permeability, and inadequate resistance to chemicals. Concrete constructions are vulnerable to sudden degradation and catastrophic failures as a result of the brittle characteristics of this material, which is widely acknowledged [1]. Scientists are improving OCC's mechanical properties by incorporating other materials, like micronized chemicals or polymeric materials.

Two different categories of Concrete with high performance can be classified by depending on its excellent mechanical characteristics in comparison with traditional fibre reinforced concrete. These categories include specific types of strain –hardening–composites (SHC) concrete, engineering -cementitious-concrete (ECC), and high-performance-fibre-reinforced-composites (HPFRCs). These materials demonstrate exceptional resistance to compression and remarkable ability to tensile ductility [2]. (ECC) concrete is an high performance-fiber-reinforcing-concrete (HPFRC) developed using the basics of micromechanical [3]. Some ingredients possessing flexibility and superior strength, which have been created and studied in depth to solve the problem of traditional concrete which is a brittleness state [4]. These materials exhibit behavior characterized by an increase in resistance to softening, known as deflection hardening, due to the production of many closely positioned micro-cracks during the process of deformation. ECCs exhibit a considerably greater ability to withstand tensile strain than traditional concrete, With a strain capacity which higher than traditional concrete, depending on the specific fiber type, properties of matrix, and interface characteristics [5]. On the other hand, traditional concrete typically has a limited ability to resist bending, with a strain capacity of approximately 0.01%. When it fractures, it forms a confined crack that extends infinitely wide [6].

Engineering cementitious composites (ECC) concrete is a series of concrete created in the past few decades. It may be described as a composite material with a significant amount of cementitious materials (silica fume and cement), a low ratio of water to binder, and the exclusion of coarser aggregates [7]. The ECC is extensively utilized in infrastructure engineering due to its exceptional material qualities, including remarkably low permeability and high mechanical properties [8]. Nevertheless, these plain cementitious materials exhibit more brittleness than regular concrete since they possess a high resistance to compressive but a poor tensile strength and strain capacity. Currently, the most efficient approach to enhance concrete's ductility is by using fiber reinforcement [9].

Polymer, glass, Steel, and carbon -based fibers are frequently used to strengthen ECC materials [10-11]. The distribution characteristics of fibers greatly affect mechanical characteristics of concrete which fiber-reinforce under tensile and modulus of rupture loadings [12]. Therefore, the size and type of fibers contribute as a crucial role in establishing these qualities.

The initial concept was based on micromechanical principles, incorporating a small quantity of pliable fiber [13-14]. Polymer fibers like PVA fibers were commonly included for their even distribution and substantial bridging impact on cement pastes [15]. PVA fibers have hydrophilic nature, as shown in Figure 1, which demonstrates for high reaction with cement composite. This is owing to the abundance of hydroxyl-groups (OH) that can serve as a reinforcing-filler [16-17]. It was crucial to establish an increment in chemical interaction between PVA fiber and the cementitious mix for obtaining superior ductility and strength in the design of (ECC) concrete [18]. The water-attracting property of PVA fiber substantially affects uniform dispersion of fibers within the mix [19]. The significance of rheology, including the workability of ECC concrete, was regarded crucial in obtaining the desired mechanical properties of the (ECC) concrete [20].

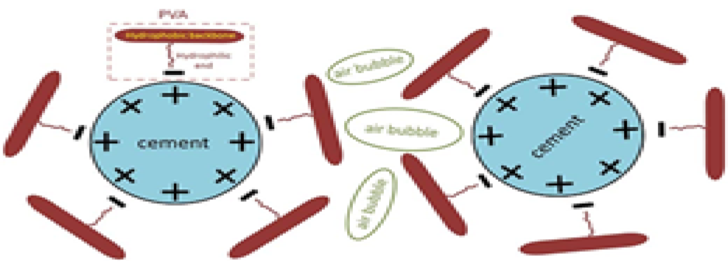

Fig. 1. Mechanism of hydrophilic effect of PVA fiber, derived from [21].

ECC-PVA concrete is suitable for applications that experience seismic and impact stresses because of its exceptional deformation capability and energy absorption. Fibers have been utilized in structural reconstructions and repairs, acting as supporting elements for high-rise construction's connecting beams and joint less bridge decks [22-24]. Previous studies indicate that the maximum strain of (ECC - PVA) concrete can vary from (3 to 8) % [25-26], in which the crack width smaller than one hundred micro-meter [27]. ECC-PVA concrete exhibits strain-hardening behavior and can be easily processed using conventional equipment. It has a strain capacity of approximately (3 to 5) %, compared to traditional concrete's (0.01) % strain capacity. ECC-PVA concrete is a distinct category of high - performance - composites with exceptional ductility and durability. Jang et al. discovered that using polyvinyl alcohol fibers greatly improved the flexural resistance of the concrete. Despite its higher cost than other fiber kinds, ECC-PVA concrete offers exceptional performance as a material for concrete reinforcement and repair, which might somewhat compensate for its expense. Therefore, PVA fiber can enhance the brittleness of ECC-based composites [28].

A theory derived from fracture mechanics and micromechanics, cementitious material is developed with distinct massive tensile plasticity properties. Therefore, ECC-PVA concrete is not a fixed material type; however, it is a broad variety of subjects under completely various phases of analysis, development, and implementation. The production and formulation of ECC-PVA concrete needs extra work by design the material in a planned way at Nano, Micro, Macro, and Composite scales [29].

Incorporating fibers into concrete enhances its modulus of rupture. The ECC-PVA concrete is created by incorporating 2% of various fibers by optimal volume. This type of concrete can flex without fracturing due to the interaction between fibers, sand, and cement. These ingredients work together within the material's matrix to bind everything tightly. PVA fibers reinforce the concrete and act as ligaments, further enhancing bonding. As a consequence, the material experiences micro-cracking rather than fracturing. This particular occurrence is characterized by the transfer of tensile strain energy into a number of microscopic cracks, each of which has a width of less than sixty micro-meters. These cracks are approximately half the width of a human hair [30].

ECC-PVA concrete utilizes ultrafine silica sand and tiny Polyvinyl Alcohol PVA fibers coated with an extremely thin layer of silk, measuring only a few nano-meters in thickness. This surface coating enables the fibers to initiate slippage when subjected to excessive loads, hence preventing fracture. It serves to prevent the fiber from rupturing, thereby eliminating the occurrence of substantial cracking. Thus, ECC-PVA concrete demonstrates a considerably greater ability to deform without fracturing, while maintaining its structural integrity, compared to traditional concrete [31].

The theory of fracture mechanics asserts that cementitious composites properties (fracture toughness and fracture energy) are crucial indicators for assessing materials fracture performance. It can indicate the difficulty of crack growth in matrix materials. Due to brittleness of concrete material; incorporating fibers into concrete can enhance its fracture resistance. The fiber acts as a bridge, effectively reducing the occurrence of cracks in micro scale and macro scale in the matrix. This helps control the matrix's cracking and enhances its toughness [32]. The degree to which the fiber acts as a bridge is primarily influenced by adhesive interaction within the interface between fiber and other ingredients, as well as the mechanical gripping force [33]. The fiber's behavior of bridging also depends on the fiber type and quantity. Polyvinyl alcohol PVA fibers are frequently incorporated into cementitious composites. PVA fiber possesses the attributes of a high strength, high elasticity, resistance to acid and alkali, and a reduced cost compared to a different fibers.

By using scanning electron microscopy, SEM, Bezerra et al. [34] investigated where the PVA fibers being distributed throughout the cementitious composite matrix. According to their findings, PVA fibers were uniformly dispersed across the cementitious composite matrix, and a significant portion was firmly linked to the matrix [34]. One of the most vulnerable areas of the concrete-aggregate interface is the “interfacial “transition zone” (ITZ). Therefore, compared to the bulk paste, the (ITZ) is described by high porosity and a high concentration of calcium hydroxide ($Ca(OH)_2$). Around (30 – 50) μm in thickness, the interfacial transition zone extends from the aggregate surface [35]. Because of this porous zone's presence, concrete's strength and durability can be compromised, and its fracture properties can be affected. Nevertheless, it was shown that the existence of PVA fibers can narrow the thickness of the (ITZ). In addition to increasing the concrete durability, decreasing (ITZ) thickness, which diminishes water absorption, is a sign of restricted permeability [36].

The inquiry into the emission of acoustic wave’s frequencies that occur during the deformation of concrete materials, as well as the propagation of concrete damage and fractures, can be utilized to ascertain the developmental and evolutionary principles of cracks in concrete materials. The loading process of concrete can be easily and quickly assessed using acoustic emission detection technology, which can also be used to identify the types of cracks, the damage degree, and locate the source of the cracks. Therefore, the technology of acoustic emission detection is crucial for the continuous monitoring and damage warning of concrete structures. Jingjun Li et al. [37] employed acoustic emission detection technology to demonstrate a failed process, fiber linking, and slipping mechanism of a composite material reinforced with PVA fibers during a bending test., as a result of the reasons mentioned previously.

To prevent fiber slippage is essential to prevent the development of substantial cracking. Hence, elastic concrete demonstrates a markedly greater level of deformation in comparison to traditional composite while maintaining its integrity of the structure without experiencing fracture. Concrete is made up of several different components, all of which work together to balance out the weight that is applied. ECC-PVA composite has exhibited a substantial increase in flexibility compared to traditional concrete, with a 50-time improvement [38]. The present investigation analyzes the influence of fiber volume (Vf) % on compressive strength, modulus of rupture, energy absorption behavior, and fracture parameters of ECC-PVA concrete. PVA fibers were added to the concrete mix at different Vf from control mix (0) % fiber to (2) % fiber with a constant (Vf) increment every (0.5) % in order to produce engineered cementitious composite ECC-PVA concrete with two grades of compressive strength, 25 [MPa], and 65 [MPa]. Applying prior studies, the mix design was evaluated by Professor Victor Li [38].

The originality of the research is derived from the utilization of locally available sand, which is classified in zone two of the Iraqi specification, as well as eliminating coarse aggregates, to produce results regarding the compressive resistance, modulus of rupture, and fracture parameters of ECC-PVA concrete mixtures. This investigation also focuses on assessing ability of PVA fiber and silica fume to withstand strain capacity and fracture parameters, specifically in terms of fracture toughness, fracture energy, and characteristic length. These properties are crucial for understanding the behavior of these materials in the composite and the principles behind bridging.

2 General Characteristics

2.1 The ECC-PVA Concrete Materials

ECC-PVA concrete can be considered a material with an extent of tensile strength and ductility which modified based on the requirements of a certain structure. It encompasses a group of ingredients that has various uses and shares the characteristics of excellent tensile flexibility and tiny different cracking. ECC-PVA concrete is specifically formulated for extensive on-site construction projects [39]. High early-strength concrete is created specifically for situations that need quick strength development, such as transportation infrastructure that must be opened promptly for public use [40]. Lightweight ECC concrete is specifically formulated for situations when it is necessary to lower the weight of structural elements due to their dead load [41]. Green ECC concrete is specifically engineered to optimize environmental friendliness and enhance the long-term durability of infrastructure [42]. Self-healing ECC concrete focuses on the ability to restore transport and mechanical properties post-damage [43].

Table 1 concisely overviews the primary physical characteristics of ECC-PVA concrete. The tailoring of ECC concrete properties can be achieved by utilizing micromechanics methods, which should be highlighted.

Table 1: Physical Characteristics of ECC-PVA Concrete Derived From [41], [44].

Compressive Resistance [MPa]	20.95
First Crack Resistance [MPa]	3 – 7
Tensile Resistance [MPa]	4- 12
Tensile Straim [%]	1 - 8
Young's Modulus [GPA]	18 - 34
Modulus of Rupture [MPa]	10 - 30
Density [g/cc]	0.95 -2.3

It is important to acknowledge that a significant amount of literature has been produced regarding ECC concrete that incorporates various types of fiber (high modulus polyethylene fibers (PE), polypropylene fibers (PP), and PVA fibers). The foundational idea behind the creation of ECC concrete in this investigation depends on utilizing polyvinyl alcohol fiber PVA fiber. However, fibers possessing particular characteristics may satisfy the requirements of strain-hardening at a reduced volume fraction. The selection of fiber to employ in ECC-PVA concrete will be determined by their inherent features, such as mechanical strength, diameter range, and surface characteristics. These properties will ultimately affect the concrete's mechanical properties, durability, and sustainability performance [44], [45].

2.2 Tensile Characteristics

This ductile behavior as approximately similar to metal behavior has a distinctive "yield point" near the end of the elastic-stage when the specimen shows signs of microcracks for the first time. An increment in force causes a response characterized by an increase in strength and hardness due to plastic deformation, which defined as an increment in both load and tensile deformation (volumetric straining with many micro-cracks instead of a single, larger crack). Once a fracture plane is formed by one of the many cracks, the specimen ultimately fractures. The high tensile ductility is very helpful for making the ultimate limit state (ULS) of a structure better in terms of its load, bending capacity, and ability to absorb energy [46].

As illustrated in Figure 2, multiple micro-cracking is essential for achieving high tensile ductility in composites. During the deformation of the material, the size of micro-crack openings gradually increments from (0 to approximately 60) micrometer, occurring the initial cracking strain of roughly (0.01 and 1) % strain. Continuing to load beyond (1) % leads to multiple cracks, but these cracks do not open further after reaching the steady-state value of sixty micrometers. The mechanics of the interlocking of the fibers with the matrix in (ECC) concrete illustrated in Figure 3.The fixed width state of crack in a material is an inherent characteristic that remains constant regardless of external factors like as loading (tension, bending, or shear), the shape and size of the structure, and the type and amount of steel reinforcement. This stands in contradiction to the production of concrete or fiber-reinforced concrete (FRC) [47].

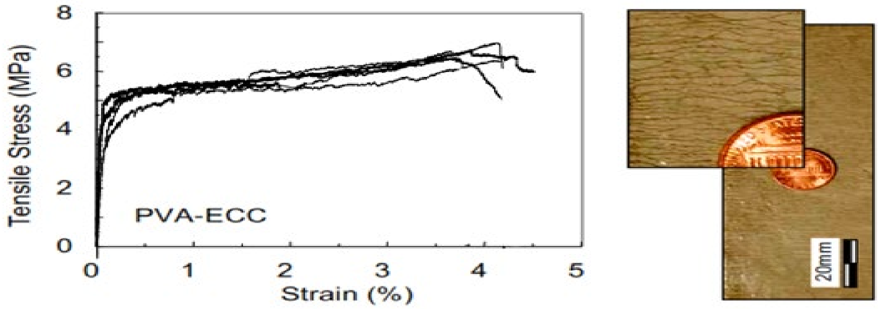

Fig. 2. Stress-Strain relationship for ductile ECC-PVA Concrete, derived from [48].

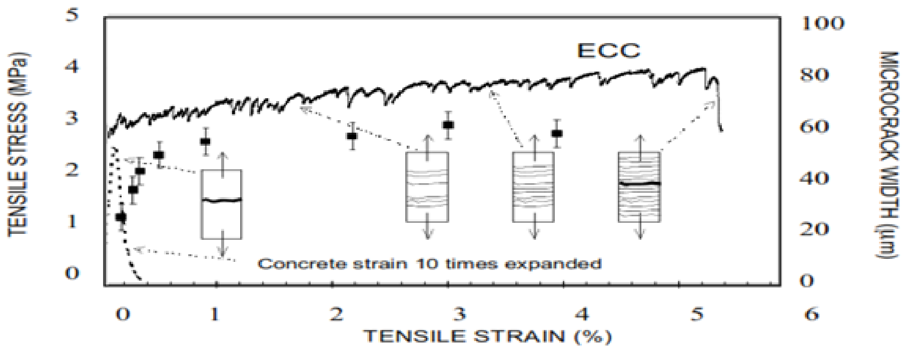

Fig. 3. The expansion of crack width in ECC-PVA Concrete in the presence of Load, derived from [47].

2.3 Design Considerations of ECC-PVA Concrete Material

ECC has been enhanced using micromechanics to obtain high ductility and narrow micro-crack width while preserving low fiber percentages (2% or less by volume). Micromechanics are a field of mechanics that focuses on the behavior of materials at the smallest level, specifically looking at how the mortar composite, fiber, and the interfacial between them interrelate mechanically. Fibers are generally several millimeters long, with a diameter of tens of microns, and have a nanometer-scale coating of surface. In ECC concrete, matrix heterogeneities such flaws, sand, cement, and mineral additive particles range in size from nanometers to millimeters. The micromechanics model should ideally cover all change in shape mechanisms at millimeters, micrometers, and nanometer scales [49].

Micro-cracks initiation occurs when the composite material develops small cracks at the initial flaw sites that is, prior to the tensile load exceeding the fibers maximum capacity to extend through the cracks in the structures. Fiber rupture, slippage, and pull-out are associated with fiber failure. To promote the growth of new fractures, it is critical in order to maintain the maximal fiber bridging capabilities on those crack planes that are already present, which are greater than the matrix breaking strength? The conventional shape of Griffith cracking is un-conducive to numerous cracking. Cracks commencement in Griffith-type cracks, particularly at center point of the crack line, consistently enlarges as the crack length increases. Invariably, failure of the linking fiber occurs either as fiber dislocation or fracture. The sole method of averting this is to modify the Griffith crack dissemination mode to a planar crack mode of propagation, in which the crack elongates while maintaining a constant crack widening at every point (except for a small linking vicinity adjacent to the crack tip), Irrespective of the crack's length [49].

2.4Compressive Resistance and Modulus of Rupture Characteristics

Compressive resistance characteristics of ECC-PVA Concrete do not exhibit significant variations compared to conventional high-strength concrete, it typically varies between 30 and 90 [MPa]. The elastic modulus of this material is approximately 20-25 [GPA], which is less than concrete because it lacks coarse aggregates. On the other hand, Compared to regular concrete, ECC-PVA Concrete exhibits a comparatively greater compressive strain capacity. Figure 4 displays a strength development curve for a grade M45 ECC-PVA Concrete. The behavior of ECC-PVA Concrete after reaching its peak strength under compression is characterized by a gradual descent, in contrast to high-strength concrete; this decline is escorted by a progressive expansion of the specimen, rather than an abrupt and explosive crushing collapse [50].

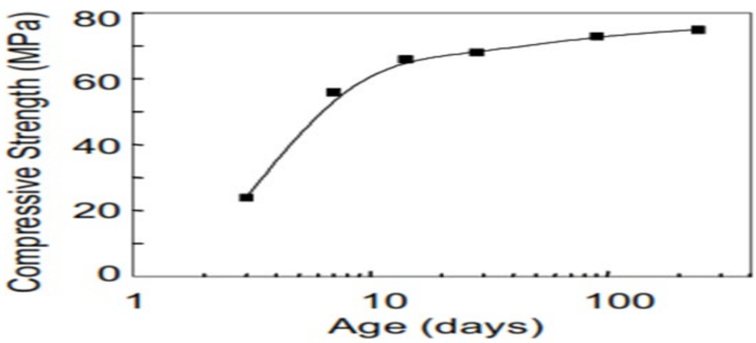

Fig. 4. Compressive strength enhancement with ages of ECC-PVA Concrete (M45) after Neville [50].

The flexural behavior of ECC-PVA concrete demonstrates its ability to deform under tension. During the process of bending, the base of the sample beam experiences the imitation of many micro-cracks, which enables it to undergo significant curvature development. This feature has led to the commonly used term "ECC-PVA" concrete [51]. It is easy to attain a flexural strength between 10 and 15 [MPa] and a substantial deflection hardening state. ECC-PVA concrete possesses the intrinsic property of deflection hardening, which is geometry-independent. Figure 5 shows an ECC beam that has been fully deformed and has small multiple cracks on the side that is being expanded [52].

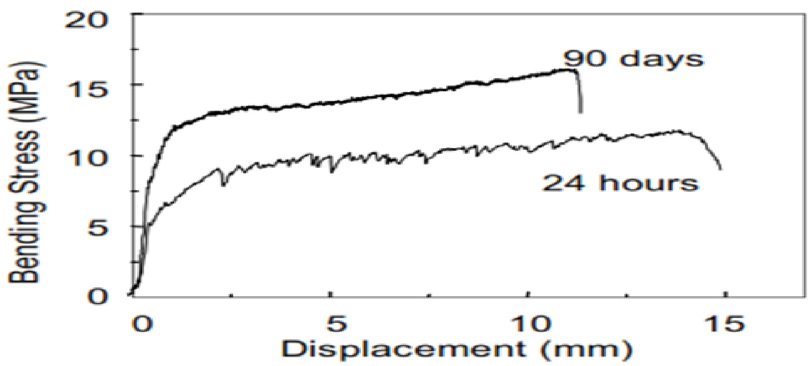

Fig. 5(a). Load-displacement chart of ECC-PVA Concrete.

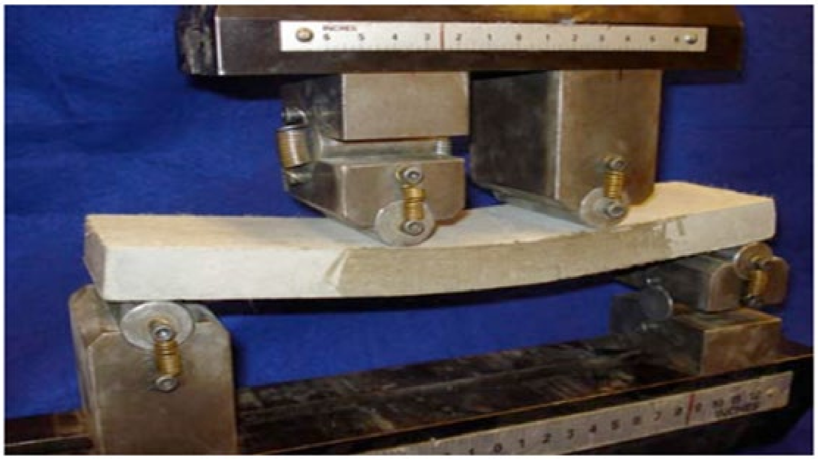

Fig. 5(b). ECC-PVA Concrete specimen showing large deflection under modulus of rupture test.

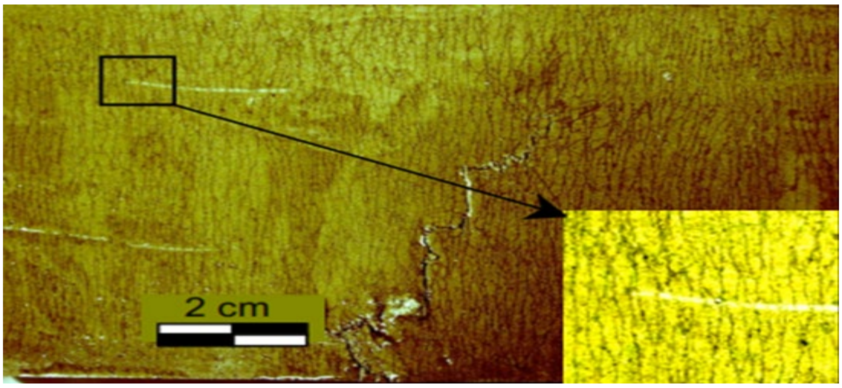

Fig. 5(c). Finer multiple cracks on the tension side of the sample, derived from [40].

3 Experimental Programs
3.1 Materials and Properties
3.1.1 Cementitious Materials

OPC (Type I) was constantly employed for the experimental work. The cement main compounds meet the requirements of Iraqi Specification No.5 [53]. Moreover, its fineness was more than 2300 [cm2/gm], soundness was 0.12, and the loss of ignition and saturation of lime factors was less than 3% and 1%, respectively. Moreover, the silica fume (SF) “Mega Add MS (D}” has a strength activity index (SAI) of (112.8) %. Physical and chemical characteristics are demonstrated in Tables 2 and 3 and conform to requirements outlined in ASTM C 1240 [54].

Table 2: Silica Fume Physical Requirements [54].

No.	Accelerated pozzolanic (SAI) after 7 days	Specification Limits
1	112.8	Minimum, 105

Table 3: Silica Fume Chemical Requirements [54].

No.	SiO_2 %	Loss On Ignition %	Moisture content %
1	92.84	1.59	0.33
Specification Limits	Minimum, 85 %	Maximum, 6%	Maximum, 3%

3.1.2 Fine aggregate

The experiment made use of natural sand as the fine aggregates. Table 4 clearly illustrates characteristics of natural sand. Figure 6 shows the sand gradation test findings falling in zone two; the sulfate percentage is 0.37%. These numbers are within the ranges specified in Iraqi requirements No. 45 1980[55].

Table 4: Natural Aggregate Properties.

Size of Sieve [mm]	Weight of Passing Sand [%]	Boundaries of Spec. (No. 45/1984) [Zone (2)][55]
9.51	100	100
4.75	98	90 - 100
2.36	89	75 - 100
1.18	77	55 - 90
0.6	55	35-65
0.3	21	8-30
0.15	5	0-10
Fineness Modulus = 2.8		
Property	**Test Results**	**Limits of Spec. No.45/1984)**
Specific gravity	2.6	-
Density, [kg/m3]	1712	-
Content of Sulfate, [%]	0.37	≤0.5
Absorption, [%]	3.2	-

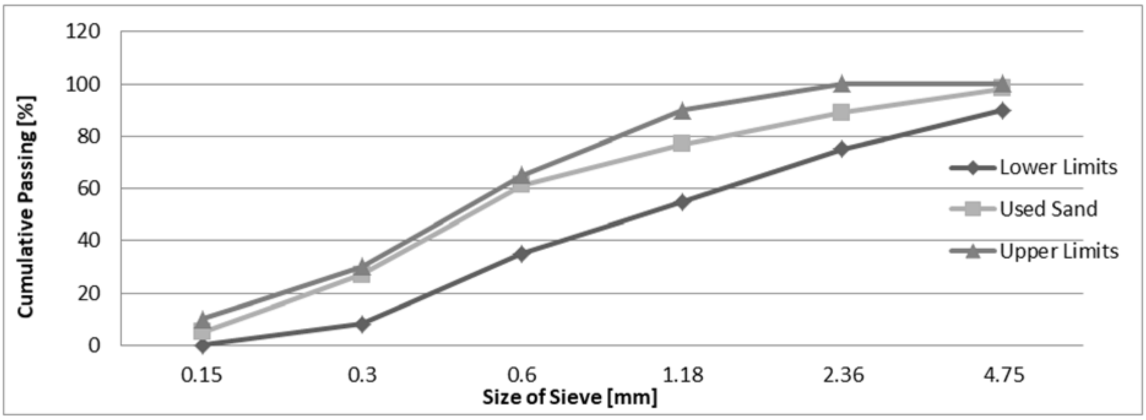

Fig. 6. Grading Curve for Used Fine Aggregate.

3.1.3 Admixture (Super-plasticizer)

SIKA Construction Chemicals manufactured Visco-Crete 5930, a high-performance super-plasticizer addition based on modified polycarboxylate. This additive was utilized in the construction project. The recommended dosage by the manufacturer ranges from 0.2 to 0.8 [liters by weight of cement]. This mixture conforms to requirements of ASTM C494, G and F [56].

3.1.4 Polyvinyl Alcohol Fiber PVA

The primary characteristics of PVA fiber are its high tensile resistance and high elasticity, non-toxicity, resistance to acid and alkali, and its ability to interact with cement readily. This study utilizes high-strength polyvinyl alcohol PVA and short fibers with a high elastic modulus, which are supplied by the factory of Sichuan Vigny Nylon. The physical characteristics are presented in Table 5, while Figure 7 illustrates the PVA fiber.

Table 5: Physical Characteristics of PVA Fiber.

Characteristics	Unit	Value
Diameter	mm	0.04
Length	mm	12-32
Tensile Strength	MPa	1600 – 2500

Density	Kg/cm3	1310
Melting Point	℃	225
Young Modulus	GPa	42.8
Specific Heat	J/gK	1.68
Poisson Ratio	-	0.42
Ultimate Elongation	%	4 – 9

Fig. 7. Polyvinyl Alcohol PVA Fiber.

3.1.5 Polyvinyl Alcohol Solution PVA

This substance is a synthetic compound that can dissolve in water and break down naturally over time. It is a dehydrated substance available in granular and powdered states. The PVA solution is an adhesive that exhibits exceptional bonding strength, the ability to create a film, and the capacity to emulsify. PVA solution can be made using the procedure outlined by Flinn Scientific [57]. Figure 8 displays both PVA powder and PVA solution. The characteristics of the PVA powder supplier are shown below by Bouling Chemical Co., Limited [58].

Fig. 8 (a). PVA Powder. (b). PVA Powder after Dissolved, derived from experimental Mix Proportion of ECC-PVA Concrete.

This study focuses on producing ECC-PVA concrete by utilizing water to cementitious (w/cm) ratio of 0.41 for M25 in addition to 0.3 for M65, which representing the compressive strength after 28 days. The PVA fiber was added to the cementitious materials at weight percentages of 0.5%, 1%, 1.5%, and 2%. Mixes were formulated with PVA fibers to get a compressive strength of 25 [MPa], also 65 [MPa] after 28 days. These fibers enhance strength and increase strain, while the flow table measurement was set at 100 ± 10 mm. The super-plasticizer dosage was modified to achieve the required level of flow-ability. Workability was tested by using flow table test for evaluation flow-ability of freshly mixed composite by pouring it into moulds and compacting it using a vibrating- table. After getting out of the mould, the samples were cured by putting them in water that was enriched with lime and kept at a degree of 20 ± 2 °C up to the date of testing. ECC-PVA is a type of mortar- composite that contains a higher amount of cementitious material with lagging coarse aggregates compared to ordinary concrete [59]. The fundamental concept behind mixed design of ECC-PVA is depended on the micro-mechanics opinion, which is based on how fibers and structures interact with each other. This caused a bridge effect that made it stronger. The best mix quantities for ECC-PVA concrete found in previous research were used as a guide for the present investigation [38]. Table 6 provides a visual representation of the ratios used in the blends. The purpose was to produce a blend with advantageous rheological characteristics by using chemical additives and Polyvinyl Alcohol PVA Solutions, resulting in practical combinations.

Table 6: Ingredients of ECC-PVA Composite of M25 and M65.

Mix ID	Cement	Sand	Silica Fume [%]	PVA Fiber [%]	PVA Solution [%]	HRWRA [%]	Water/Binder Ratio
L-BC0	1	0.8	10	0	0	1	0.41
L-BC0.5				0.5	1	1	
L-BC1				1	1	1.2	
L-BC1.5				1.5	1	1.4	
L-BC2				2	1	1.4	
H-BC0	1	0.8	10	0	0	1.3	0.3
H-BC0.5				0.5	1	1.3	
H-BC1				1	1	3	
H-BC1.5				1.5	1	4	
H-BC2				2	1	4	

A mixing container with 0.15 [m3] used to prepare the ECC-PVA composite mixtures. The duration of all necessary works, as well as the segments of the mixing procedure, are presented in Table 7 [60]. The total time for preparing the mixture is about (7–8) min.

Table 7: Mixing Procedure Steps of ECC-PVA Concrete.

Step No.	Step Details	Duration [Min]
1	Mixing dry components (cement, silica fume, and fine aggregate).	2
2	Water in addition to super-plasticizer is mixed together followed by added slowly into the dry components.	2
3	Mixing is maintained, PVA Solution and fiber are slowly added to the mix and then mixing until the PVA fiber has adequately dispersed to avoid clumping.	3

Once the final preparation is complete, the newly prepared mixture is put into molds and compressed on a vibrating table. The compressive resistance was tested on (90) cubes with side of 100 [mm], modulus of rupture was tested on (90) prisms with dimensions (100×10×400) [mm], and fracture parameters were evaluated on beams that gave the higher flexural strength for each grade of strength. All beams were tested by initiating a notch (pre-crack) by fixing a plastic plate in the middle of the tensile lower face with a thickness of (2) mm before casting. A constant notched-to-beam depth ratio (ao) of 0.2d was taken. Upon completion, the samples were enveloped with moist cloth and placed in the casting room at a temperature of (20 ± 2) 0C. Subsequently, the samples were taken away from the moulds after 48 hours and immersed in a water tank for duration of 90 days to evaluate their compressive resistance and modulus of rupture. Additionally, the fracture characteristics were assessed after 28 days.

4 Experimental works and Analysis

4.1 Fresh Properties

To obtain ECC-PVA concrete with good mechanical properties, water to cementitious (w/cm) ratio is essential in defining the composite's strength. Reducing the amount of water relative to cement in ECC-PVA concrete is anticipated to enhance the strength of the mixture and facilitate uniform distribution of fibers and uniformity of the mix. Nevertheless, excessively decreasing this ratio might also diminish the workability of the concrete. Research indicated that a (w/cm) ratio of 0.27 provided the most favorable outcome. Maintaining the (w/cm) range from 0.22 to 0.34 is advisable. This is because a ratio over 0.34 can result in increased strain hardening and reduced strength. To achieve possible equilibrium between strength and workability, a (w/cm) ratio of 0.41 is required, as supported by previous research [59]. Also, Consistent dispersion of PVA fibers is required. The uniformly distributed composites can be obtained by utilizing a small amount of fiber to the blender many times, prolonging the mixing time appropriately, and using a high-speed shear-action mixer. The flow table analysis was carried out using the advised procedures which according to ASTM C-1437-15 [61]. The present work evaluated the flowability of ECC-PVA concrete mixes. Table 8. And Figure 9. Represent values of flow table. Higher percentages of PVA fibers cause a decrease in flow table values, which results in increased internal friction and water absorption among concrete constituents. The use of (HRWRA) improved the workability of concrete that contained PVA fibers. Furthermore, the presence of PVA solution had an impact on the viscosity of the ECC-PVA concrete mixture. To enhance the consistency of the mixture, a solution of polyvinyl alcohol PVA was incorporated to increase its viscosity.

Fig. 9. Flow Table Test.

Table 8: Results of Flow Table Test.

Mixes Symbol	Spread Dia. [mm]	Flow [%]
L-BC 0	212	112
L-BC 0.5	202	102
L-BC 1	195	95
L-BC 1.5	170	70
L-BC 2	158	58
H-BC 0	210	110
H-BC 0.5	193	93
H-BC 1	174	74
H-BC 1.5	162	62
H-BC 2	146	46

The density of fresh mixture was estimated by utilizing the mean of three cubes with dimensions of 100×100×100 [mm]. This examination was conducted in accordance with ASTM C567/C567M–19 [62]. When compared with a traditional mixture, the fresh density of M25 reduced due to PVA fiber addition by approximately (8.2%, 9.1%, and 11.1%) for (1%, 1.5%, and 2%) respectively. While (0.5%) of PVA fiber showed a higher density value when compared to mix with (0%) replacement. While, M65 mix containing (1%) PVA fiber had a higher fresh density value, as illustrated in Table 9. The results of fresh density decreased when the PVA was replaced by weight of cement. This is attributed to the diminution in relative density of PVA in comparison with the other substitutes of concrete; moreover, the total volume of concrete was increase by the increase in fiber addition.

Table 9: Test Results of Fresh Density.

Mix ID	PVAFiber by Wt of Cement [%]	HRWRA by Wt of Cement [%]	Density of Fresh Mix [kg/m3]
L-BC 0	0	1	2402
L-BC 0.5	0.5	1	2441
L-BC 1	,1	1.2	2203
L-BC 1.5	1.5	1.4	2183
L-BC 2	2	1.4	2135
H-BC 0	0	1.3	2540
H-BC 0.5	0.5	1.3	2520
H-BC 1	,1	3	2553
H-BC 1.5	1.5	3.4	2332
H-BC 2	2	4	2280

4.2 Hardened Properties

Dry density and absorption of water for (100×100×100) [mm] cubes of ECC-PVA concrete can be tested at (28) days, in agreement with BS EN 12390 [63] and ASTM C642-13[64], respectively. Absorption of water outcomes and dry density results are shown in Table 10 and illustrated in Figures 10 and 11. The air-dried density has been found to increase as PVA fiber content increases, up to a level of 1.5%, due to the great effect of curing for continuous hydration product and strengthening the (ITZ). Furthermore, the fibers are coated by $Ca(OH)_2$ products, which increments the density of the fiber surrounds. However, when the percentage of PVA fibers in the mixture rises, the results show a decrease due to the higher volume of fibers, but (1%) PVA fiber gave the higher value of density of M65. The enhancement in density and reduction in water absorption refers to the convenient interaction with the surrounding matrix, as a result from fiber geometric characteristics and hydrophilic nature, causing to agglomerate the $Ca(OH)_2$, which envelops the fibers, thereby enhancing the density of the fiber around, as a result of the chemical reaction between the component and un-hydrated cement, which leads to a rise in calcium silicate hydrate (C-S-H) and a decline in the generation of $Ca(OH)_2$ in the (ITZ). This results in an enhanced adhesion between mortar and PVA fiber, the same conclusion discussed by the experimental investigation implemented by Thong et al. [65]. While, the increment in PVA fiber above certain limit cause a decrease in the results due to the increment of fiber percentage which may refer to the non-homogenous distribution of fiber, fiber rupture, porosity in the (ITZ), and the lower density of PVA fiber that reduce the overall density of concrete.

Table 10: Results of Dry Density and Water Absorption Test.

Mix. Symbol	Dry Density [kg/m3]	Water Absorption [%]
L-BC0	2332	8.2
L-BC0.5	2350	7.9
L-BC1	2395	7.5
L-BC1.5	2432	6.8
L-BC2	2390	7.7
H-BC0	2359	7.8
H-BC0.5	2393	7.5
H-BC1	2565	5.3
H-BC1.5	2510	6.1
H-BC2	2430	7.2

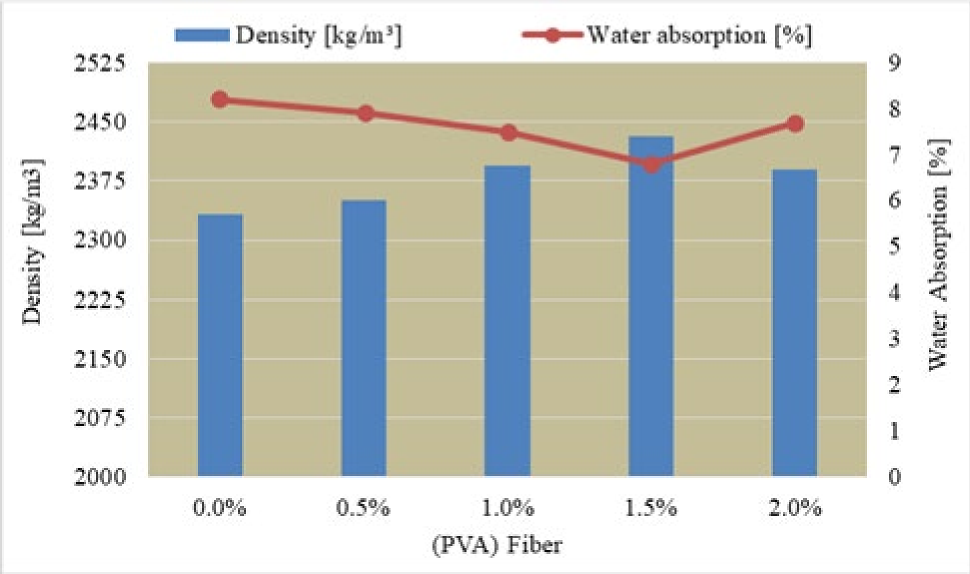

Fig. 10. Dry Density and Water Absorption Test Results of ECC-PVA Concrete for M25.

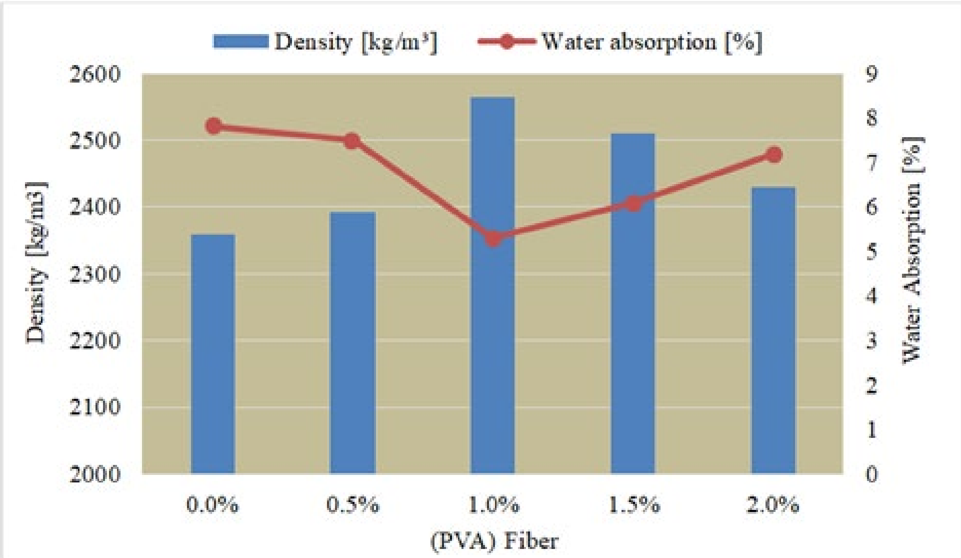

Fig. 11. Dry Density and Water Absorption Test Results of ECC-PVA concrete for M65.

Furthermore, the compressive strength of (100×100×100) mm cubes was evaluated at (7, 28, and 90) days and found to meet the requirements of BS EN 12390 [63]. Furthermore, flexural strength was determined by testing beam or plate samples of (100×10×400) mm, adopting the requirements stated in the ASTM C293-2016 specification [66]. The test findings presented in Table 11 and Figures 12-14 indicate that the strength increases noticeably as the curing process advances. The concrete mixtures containing PVA fiber exhibited greater strength results compared to the conventional mix for all test ages. This same trend is illustrated by [67] and [68]. Composite containing (1.5%) and (1%) illustrates the optimum mix for M25 and M65, respectively. The increment in resistance of ECC-PVA concrete is attributed to the capacity of PVA fiber to establish intricate clusters with the iron hydroxide present in the cement matrix. The existence of OH- and Ca+ in the paste leads to the attraction of these ions to the PVA fibers, resulting in the production of a $Ca(OH)_2$ layer surrounding the fibers. This layer plays an essential role in enhancing the interaction strength between the fiber and the matrix. Moreover, The enhancement in resistance can be associated with the chemical reaction of PVA fiber and the paste, resulting in the establishment of new substances that fill the gaps of matrix or enhance link between the cement grains.

On contrary, the flexural strength declined when the proportion of PVA fiber was above 1.5% for M25 and 1% for M65. The reduction in resistance can be related to the diminished cohesion and extremely weak adhesion of calcium-silicate-hydrate (C-S-H) gel to PVA fiber. In contrast, the results presented in Table 11 and Figure 14 demonstrate that concrete mixes containing 1.5% fiber had greater flexural strength than other percentages of fiber in 25 [MPa] grade of ECC-PVA composite. However, as replacement of fiber increment, the strength was decrease. Meanwhile, (2%) PVA fiber revealed a higher flexural strength than the other fiber percentages for M65 ECC-PVA concrete.

Table 11: Hardened Properties of ECC-PVA Concrete.

Mix. Symbol	Compressive Strength [MPa]			Flexural Strength [MPa]		
	7 Days	28 Days	90 Days	7 Days	28 Days	90 Days
L-BC0	19.1	28.5	32.1	4.1	5.5	7.6
L-BC0.5	19.7	28.9	33.4	5.2	7.2	8.5
L-BC1	21.5	32.1	36.2	6.7	8.5	9.6
L-BC1.5	24.2	35.3	40.2	8.4	9.8	10.4
L-BC2	24.1	33.9	38.4	8.1	9.2	10.2
H-BC0	44.6	60.9	63.7	9.1	10.9	11.1
H-BC0.5	46.7	63.7	66.9	11.2	13.2	14.1
H-BC1	49.1	66.3	70.3	13.2	15.1	16.9
H-BC1.5	47.5	65.1	68.2	14.5	16.9	17.5
H-BC2	46.9	64.3	67.4	16.7	19.1	19.9

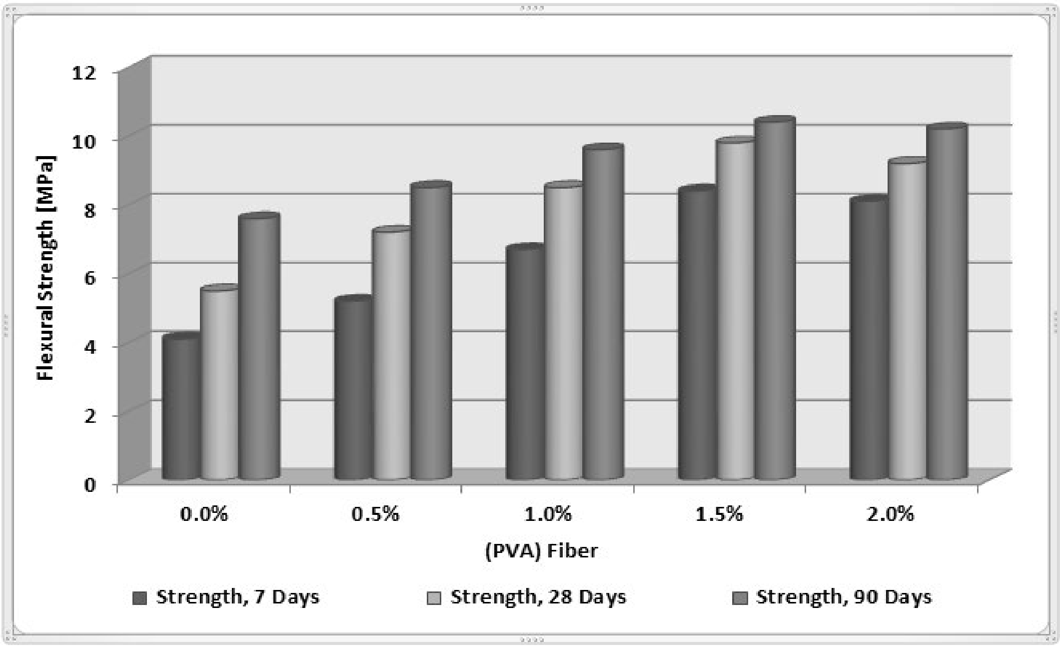

Fig. 12. M25 Compressive Resistance Test Results at 7, 28, and 90 Days Age.

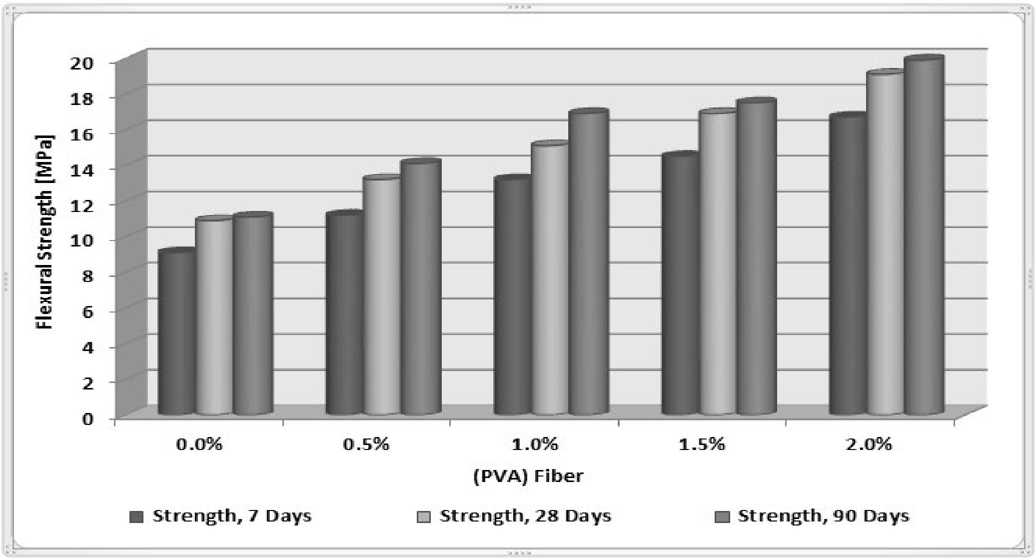

Fig. 13. M65 Compressive Resistance Test Results at 7, 28, and 90 Days Age.

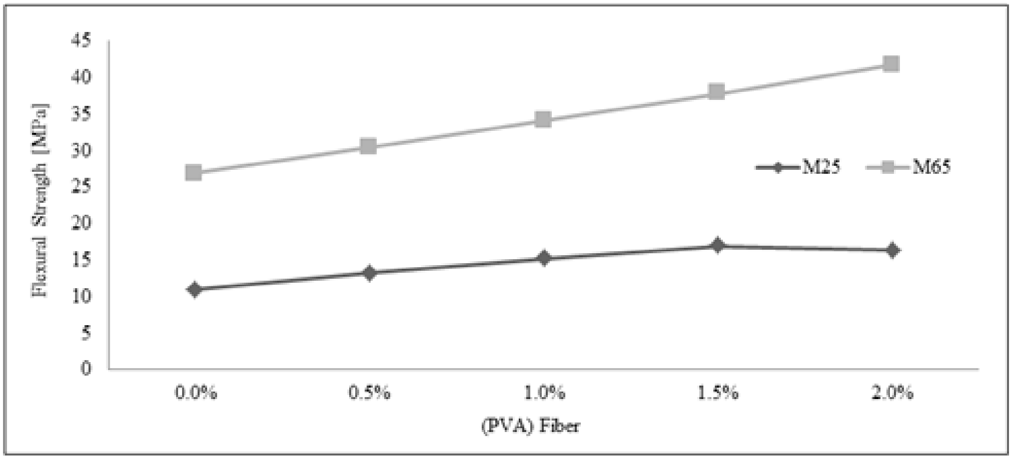

Fig. 14. Flexural Strength of ECC-PVA concrete Containing Different PVA fiber at 28 Days Age.

Finally, the optimum mix, which gave the higher flexural strength for both grades of strength, was optimized for evaluating the fracture parameters; three notched beams under three-point bending testing machine of geometrically similar dimensions was made by following the RILEM TC-89 [69] to study the size effect on fracture toughness, fracture energy, and characteristics length. The optimum mixes which gave the higher flexural strength of (1.5%) and (2%) of PVA fiber for ECC-PVA concrete mix with M25 and M65, respectively. Different sizes of each notched beam were made; the information of the beams dimension are illustrated in Table 12.

All notched (pre-crack) beams were constructed by fixing a metal plate in the middle of the tension face with a constant thickness of (2) mm before casting, which was chosen according to [70]. The higher load should reach nearly about six minutes by used rate of loading of (0.2) mm/min.

Table 12: Notched Beam Dimensions and Number of Samples.

Mix ID	Target Comp. Strength	PVA fiber %	Notched Beams Size mm					No. of samples
			Length L	Width B	Depth h	Depth Ratio	Notch Depth ao	
M25-BC1	25	1.5	400	75	75	0.2	15	3
M25-BC2			800	75	150		30	3
M25-BC3			1200	75	200		40	3
M65-BC1	65	2	400	75	75	0.2	15	3
M65-BC2			800	75	150		30	3
M65-BC3			1200	75	200		40	3

Bažant's stress-relative deflection curve and Bažant's size effect law were employed to examine the impact of size on ductility and strength [71], [72]. The investigation of the impact of size on flexural behavior and toughness was conducted using BS EN 14651 [73] and ASTM C1609 [74], respectively. The size effect on fracture energy was studied using RILEM TC-50 FMC [75]. The investigated fractures parameters can be summarized as, firstly, fracture toughness KIC, which characterizes the stress field surrounding the fracture plane. Equation 1, used to measure the stresses at the crack tip, K, is given by Brown and Strawley [76].

$$K_{IC} = Y\frac{6Ma^{0.5}}{bd^2} \quad (1)$$

$$Y = 1.99 - 2.47\left(\frac{a}{d}\right) + 12.97\left(\frac{a}{d}\right)^2 - 23.17\left(\frac{a}{d}\right)^3 + 24.8\left(\frac{a}{d}\right)^4 \quad (2)$$

Where: Y: Function of Geometry, unit less. K_{IC}: Fracture Toughness, MPa.mm$^{1/2}$. M: Bending moment due to maximum applied load, N/m. b: Width of beam, mm. d: Depth of beam, mm. a: Notch depth, mm.

Secondly, the energy required for creating a unit crack surface which is calculated as the work done during fracture divided by the uncracked ligament's region [77], [78]. The area under of the load-displacement curve of the notched beam was calculated and applied by equation 3 to find fracture energy. GF can be specified indirectly by 3-point bending test using RILEM TC50-FMC [79]:

$$GF = \frac{W_0 + m.g.\delta_{max}}{A_{lij}} \quad (3)$$

Where: W_o: Is the external work corresponding to the area under the load-displacement curve, N.mm. m: The mas of the beam between the supports. Kg. g: The acceleration due to gravity, 9.81 m/s^2. δ_{max}: Maximum displacement, m. A_{lig} : Fracture area, [b(d-a_o)], m^2. b: Width of beam, mm. d: Depth of beam, mm. a_o: Notch depth, mm.

Finally, Hillerborg et al. [80] proved equation 4 to illustrate the fanciful crack model's characteristic length (l_{ch}) or brittleness number. Characteristic length is adversely proportional to brittleness number; as a degree of brittleness rises, the l_{ch} value decreases.

$$l_{ch} = (G_F * E)/f_t^2 \quad (4)$$

Where: G_F: Fracture energy, N/mm. E: Elastic moduli, GPa. f_t: Resistance of material to breaking under tension, MPa.

This investigation used a three-point bending load test to evaluate KIC, GF, for (36) notched beams. The ao/h (notch depth/beam depth) ratio was 0.2, while the L/h (distance between support/beam heights) ratio was 5. In accordance with the fracture parameters observation, as illustrated in Table 13 and Figures 15 and 16, the research findings are as follows:

- The relation between loading and displacement is approximately linear for all test samples up to the ultimate load.
- ECC-PVA concrete displayed higher deflection values than conventional concrete, unlike concretes without fibers. These concretes were also less susceptible to crack presence. Also ECC-PVA concrete has a different fracturing behavior than traditional concrete with the same compressive resistance, due to its higher ductility and bonding strength. Denser interfacial transition zone of ECC-PVA concrete had a higher KIC and a ductile mode of failure with a flatter fracture plane than conventional concrete. The higher fracture toughness value was observed on (M25-BC3) and (M65-BC2).
- Furthermore, the inclusion of PVA fibers in concrete resulted in a rise in fracture energy. These fibers can withstand external loads when subjected to tension, operate as bridges, reduce stress concentration in the mix, and restrict the formation of additional cracks, as illustrated in [81]. An excessive concentration of polyvinyl alcohol PVA fibers within the matrix leads to an uneven dispersion of the fibers, resulting in fiber accumulation and the creation of significant voids in the matrix. This, in turn, negatively impacts the fracture performance of the matrix, as demonstrated by the similar trend observed in reference [82].

• All Beam results of M25 and M65 ECC-PVA concrete with different fibre volumes exhibited deflection-softening behavior. On the other hand, used (1.5 and 2) % of PVA fiber illustrated deflection-hardening.

• It is evident that during the initial loading stage, the strain value increases linearly with the applied load, resulting in the storage of elastic energy in the specimen. However, once a crack begins to form at the notch region, the strain value will continue to increase, because of storing elastic energy in the structure near the crack tip. The load associated with this point is solely the first cracking load.

• When the percentage of PVA fiber was increased between 0 and 2 [%], the fracture performance of ECC-PVA concrete showed a steady improvement, compatible with the findings of Toutanji et al. [83] and Li et al. [84]. During the process of reinforcing the matrix with fibers, the first crack in the matrix results in strain softening or localized softening. Moreover, incorporating PVA fiber facilitates bridging, enhancing hardening, and restricting crack propagation. When the external stress reaches the same level as the strength of the fiber, the fiber either is pulled out or breaks. This causes the wider crack in the matrix to open, leading to a decrease in the load (softening stage) and the creation of numerous cracks. However, in a particular investigation, it was seen that the matrix did not show several cracks, but rather only one primary break. It is possible to attribute this to the low quantity of PVA fibers, which was only 0.3%. This low fiber content might not have been sufficient to effectively bridge the fissures, as indicated by reference [85]. A higher percentage of PVA fibers results in a beneficial fiber-bridging effect, which is advantageous for crack management [84].

Table 13: Notched Beam Fracture Parameters Test Results.

Mix ID	Toughness[N.m]	Fracture Toughness[MPa.mm1/2]	Fracture Energy[N/m]	Characteristics Length[mm]
M25-BC1	5.5	27.2	1608	3014
M25-BC2	15.1	37.9	2067	3999
M25-BC3	24.5	42.2	2620	5462
M65-BC1	5.7	54.0	5247	3445
M65-BC2	24.6	71.5	6025	4519
M65-BC3	32.3	78.6	6360	5236

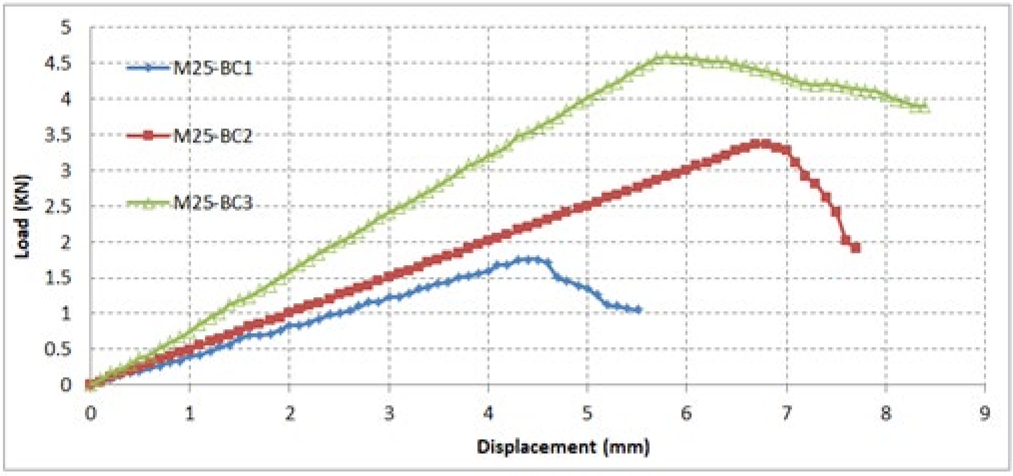

Fig. 15. Load-displacement Curve of M25 notched beams for all mixes.

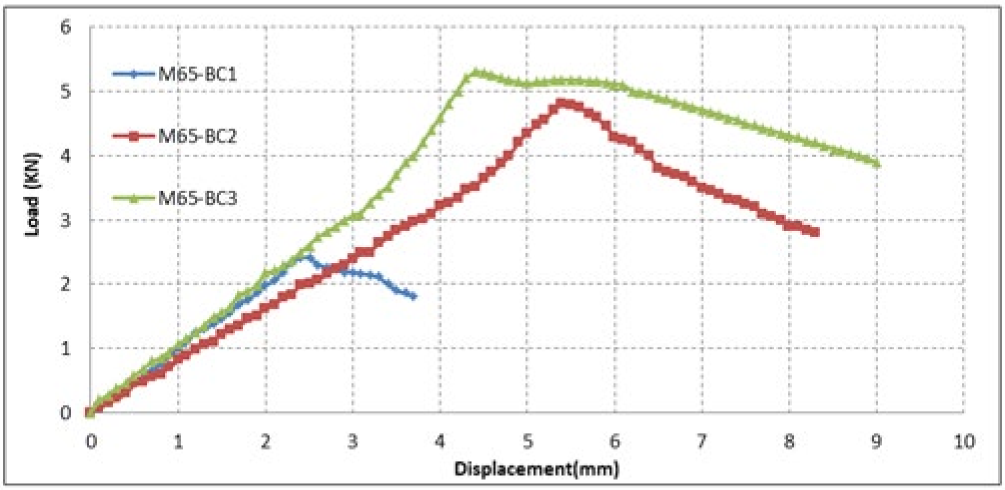

Fig. 16. Load-displacement Curve of M65 notched beams for all mixes.

5 Conclusions

The conclusions demonstrate the study's findings on the inclusion of PVA solution and PVA fiber in ECC concrete for laboratory tasks, highlighting their significance. The conclusion of these investigations is clarified through a number of distinct points:

1. The addition of a polyvinyl alcohol solution (PVA acetate) provides favourable Viscosity and rheology of ECC characteristics, while the PVA fiber has enough strength to improve the flexibility of ECC-PVA concrete.
2. The water absorption decreases gradually as the fraction of PVA fiber increases. The addition of 1.5% PVA fiber to concrete with a compressive strength of 25 MPa can reduce water absorption by 17% compared to concrete without fiber. At the same time, M65 the results show that a mix containing 1% of PVA fiber gave lower water absorption by 32 % than the other fiber percentages. Still, additional percentages of PVA fiber for both grades of strength cause an increment in water absorption results but are still lower than conventional concrete.
3. According to outcomes of ECC-PVA concrete has lower permeability of water in the existence of micro-cracks in comparison to traditional concrete cracks.
4. The density test of concrete exhibits minor variations throughout different mixtures. The ECC-PVA concrete exhibits a somewhat greater density compared to the reference mixture.
5. The fiber volume fraction has an impact on the elasticity of ECC-PVA composite. Therefore, it is clear that the concrete mixture with a fiber content of 2% demonstrates greater potential for elasticity compared to the mix with a fiber content of 1.5%.
6. The compressive strength of ECC-PVA concrete with 25 [MPa] is approximately (1.4, 12.6, 23.8, and 19)% greater than the comparable reference mix for fiber replacement levels of (0.5, 1, 1.5, and 2)% of PVA, respectively.
7. The inclusion of 1.5 and 1 % of PVA fiber represent the higher compressive resistance at (28) days for M25 and M65 of ECC-PVA concrete, respectively.
8. The utilization of PVA fiber in a mix with strengths of 25 [MPa] and 65 [MPa] resulted in an increased strain capacity due to the favourable bonding behaviour between the fibers and matrix.
9. Calculations of fracture parameters to evaluate deflection behavior of ECC-PVA concrete containing (12-32) mm long PVA fibre represent a larger deflection of about (8.4 and 9.1) mm for M25 and M65, respectively.
10. The sequential development of matrix multiple cracking results in a more significant tensile-strain behavior in ECC-PVA concrete.

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