Engineered Cementitious Composites (ECC): A Review of the Most Common Laboratory Testing Methods

Materiale Compozite Cementoase (ECC): O analiză a celor mai utilizate metode de testare în laborator

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Abstract. *Recent advancements in material research and technological innovations in the processing of raw materials for concrete production, combined with global shifts and the pursuit of sustainability, have prompted increased interest in the development of novel concrete mixtures. Despite several decades of intensive research in concrete technology, the practical implementation of these advancements remains relatively limited. This paper reviews existing testing methods and synthesizes the most relevant findings, while emphasizing the specific contributions and limitations of each study.*

Key words: *engineered cementitious composites, mechanical properties, sustainability*

1. Introduction

Concrete has been used since antiquity, most prominently during the Roman Empire and in other early civilizations, and continues to serve as an indispensable construction material in the modern era. Its inherent lack of tensile strength led to the development of reinforced concrete (RC), followed by fiber-reinforced concrete (FRC) and, more recently, engineered cementitious composites (ECC) [1].

Incorporating randomly oriented short fibers into concrete leads to notable enhancements in its mechanical performance, particularly in tensile and flexural strength, ductility, fatigue performance and resistance to impact loading [2].

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Despite their superior properties, these advanced materials face limited adoption due to high production costs, absence of standardized design guidelines, and insufficient practical knowledge. Establishing a solid research foundation and translating findings into design standards and reference materials are essential steps towards enabling the widespread implementation of ECC in construction practice [3].

The distinctive response of ECC mixtures under impact loading and tensile strain has prompted extensive research aimed at developing design guidelines for their use in protective and other structural applications. Numerous experimental and numerical studies have investigated the impact resistance of ECC elements. Recent research has primarily focused on the impact behaviour of cement-based composites reinforced with either mono-fibers or hybrid-fibers incorporating two or more fiber types. Due to the technical challenges and high costs associated with large-scale impact tests, researchers have often employed small-scale drop-weight tests, projectile impact tests, or weighted pendulum tests, despite the intrinsic limitations of these methods.

This paper reviews the predominant laboratory testing methods used to assess the mechanical properties of fiber-reinforced concrete, highlighting their key contributions and inherent limitations.

2. Classification and ECC behaviour

Engineered Cementitious Composites, along with related mixtures, are classified within the broader category of high-performance fiber-reinforced cementitious composites (HPFRCCs). The defining attributes of ECC are their enhanced tensile ductility, typically reported in the range of 3-5% strain, and their tensile strength, generally between 4-6 MPa, achieved with a fiber volume fraction of approximately 1.5-2%. Under uniaxial tensile loading, ECCs exhibit a characteristic tensile-strain-hardening response, initiated by the formation of multiple fine cracks and sustained by effective stress redistribution through fiber bridging mechanisms. The progressive development of cracks ultimately results in localized deformation and failure along a preferential plane where the tensile stress surpasses the material's capacity.

Under certain conditions, however, the formation of a single dominant crack may govern the material response during testing, resulting in tensile-strain-softening. The principal parameters governing this behaviour include the following:

- Fiber type, such as polyethylene (PE), polypropylene (PP), polyvinyl alcohol (PVA), or steel.
- Relative proportions of the primary mix constituents.
- Mixing sequence and associated processing parameters.
- Type of mechanical test employed and corresponding testing parameters.
- Fiber dispersion within the matrix.

Figure 1 presents the stress-strain and deformation responses up to failure, as obtained from uniaxial tensile tests reported by Fakharifar et al. [4].

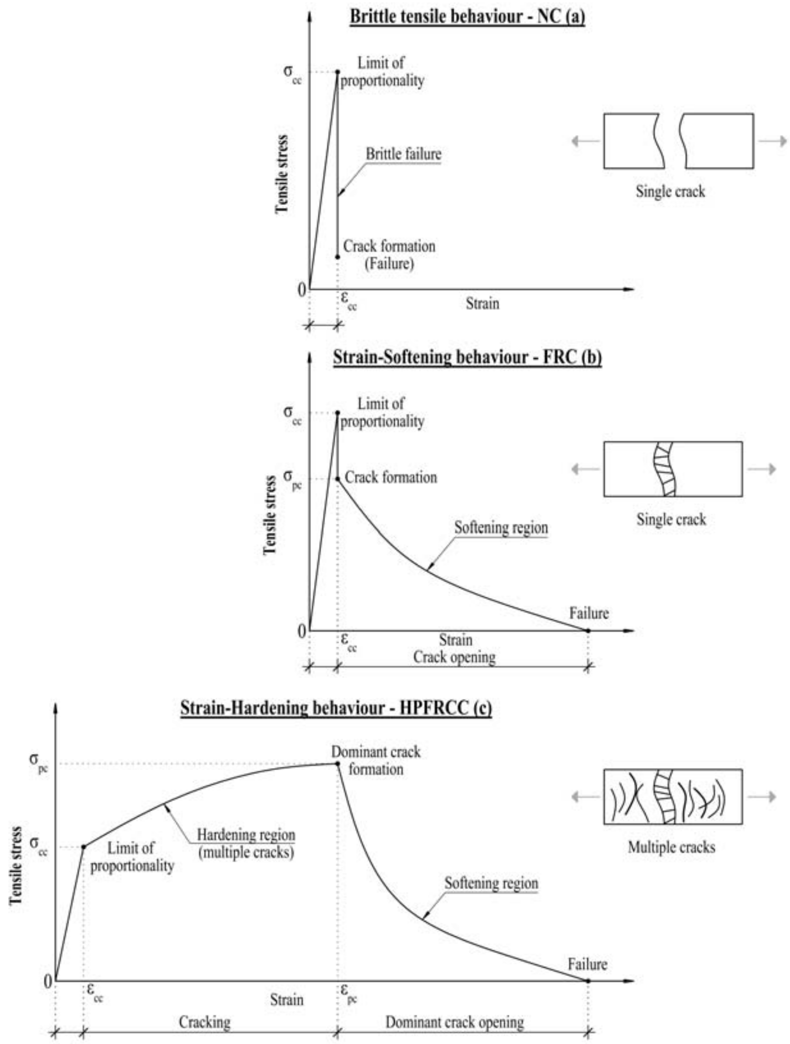

Fig. 1. Typical tensile stress-strain or deformation relation up to failure of: (a) Normal Concrete (NC); (b) Fiber Reinforced Concrete (FRC); and (c) High Performance Fiber Reinforced Cementitious Composites (HPFRCC); σ_{cc}, First cracking stress; σ_{pc}, Post cracking stress; ε_{cc}, First cracking strain; ε_{pc}, Post cracking strain.

3. Common laboratory testing methods used for the evaluation of mechanical properties

While RC is a widely adopted material and has been extensively employed in conventional construction projects in conjunction with steel, fiber-reinforced concrete has experienced relatively limited adoption and remains uncommon in standard practice. The widespread use of RC in recent decades can be attributed, in part, to the accumulation of a substantial body of knowledge and the accessibility of this information to practitioners, combined with its low production cost and broad range of applications. Moreover, governing bodies have established comprehensive standards that regulate the application, design, and conditions of use for RC, thereby facilitating its integration into mainstream construction practices.

Due to the high level of academic interest in ECC, numerous studies have been published on the mechanical behaviour and properties of these mixtures. Typically, these properties are assessed using the standard methods applied to plain concrete, namely the uniaxial compression test, the uniaxial tension test and the beam flexural (bending) test. However, because ECC exhibit significantly enhanced tensile strain capacity and superior performance under dynamic loading, these conventional tests alone are insufficient to fully capture its mechanical response. Consequently, additional testing methods are frequently employed, including the drop-weight test (instrumented or non-instrumented), the instrumented gas gun test and the instrumented pendulum test, which provide further insight into the behaviour of ECC under impact and high-strain-rate conditions. Table 1 summarizes the testing methods and outlines the distinguishing characteristics of each study.

Table 1

Summary of tests conducted in literature

Reference	Mixture type	Fiber type	Fiber content	Testing method(s)	Particularities
6	FRC	Steel and PP	0.2–1%	C, ST, DWT	Dual fiber reinforcement
7	N/A	N/A	N/A	C, DWT (I)	Crumb rubber substitute for aggregates
10	ECC	PVA and SMA	2% PVA 0-1.5% SMA	T, DWT	Dual fiber reinforcement
11	ECC	Steel and PE	0.5% and 1.5%	T, P	Dual fiber reinforcement
12	FRC	CF and HF	0.5-1.5%	F, DWT	Dual fiber reinforcement
13	ECC	PP	2%	C, F, DWT	Exposure to 500 °C
14	ECC	PVA	2%	C, T, F, DWT	Varying FA proportions
15	Concrete	Micro-steel	0.5-1%	DWT	Self-compacting concrete
16	ECC/EGC	PVA	2%	C,T, DWT (I)	Different drop heights
17	ECC	SMA and PVA	2% PVA 0-1.5% SMA	C,T, DWT (I)	Dual fiber reinforcement
18	Concrete	N/A	N/A	P	Model comparison
19	ECC	PVA and Steel	1.75% PVA 0.58% Steel	P	Dual fiber reinforcement
20	ECC	N/A	N/A	Ch	Review and commentary

FRC, Fiber Reinforced Concrete; ECC, Engineered Cementitious Composite; EGC, Engineered Geopolymer Composite; PP, Polypropylene; PVA, Polyvinyl Alcohol; SMA, Shape Memory Alloy; PE, Polyethylene; CF, Crimped Fiber; HF, Hooked end Fiber; C, Compression; ST, Splitting Tensile, T, Tension; DWT, Drop-Weight Test; DWT (I), Drop-Weight Test Instrumented; P, Penetration; F, Flexural; Ch, Charpy Test; FA, Fly Ash; N/A, Not Applicable.

3.1. Uniaxial compression test

The uniaxial compression test is one of the most widely employed material tests for concrete, primarily due to its relevance in characterizing the material's resistance under compressive stresses, which may range from 20 MPa to 95 MPa in the case of ECC [5]. In accordance with established standards (ASTM C39, EN 12390-3), the procedure involves subjecting standardized specimens – commonly cylinders or cubes to a gradually increasing load applied along a single axis, while permitting lateral deformation. The specimen is positioned between two rigid plates to ensure uniform load transfer, and the compressive force is increased at a controlled rate until failure occurs.

The principal parameter obtained from this test is the compressive strength (f_c) which is widely recognized as a fundamental indicator of concrete quality and performance. Furthermore, additional mechanical properties, such as the elastic modulus (E), may also be determined in accordance with relevant standards (ASTM C469, EN 12390-13), thereby providing a more comprehensive understanding of the material's behaviour.

One study reported a 14.4% increase in compressive strength when fibers were incorporated into the mixture to produce FRC, compared with plain concrete [6]. In contrast, another investigation examining the replacement of the aggregate with crumb rubber observed substantial reductions in both compressive strength (94%) and elastic modulus (96%) when comparing specimens with 100% crumb rubber to control specimens containing no rubber [7].

3.2. Uniaxial tension test

When considering ECC as a primary building material, its superior tensile strength (ranging from 4 MPa to 12 MPa) represents a key advantage over conventional concrete, as this mechanical property enhances crack resistance, ductility and long-term structural durability [5].

Given its importance, tensile strength is frequently employed to characterize ECC specimens and to evaluate the overall performance of the material. This property is typically measured using standardized coupon or cylindrical specimens, in accordance with the Japan Society of Civil Engineers (JSCE) [8], which are clamped at both ends and subjected to a controlled displacement rate of 0.5 mm/min in opposing directions, thereby generating a uniaxial tensile stress response. Although numerous experimental tensile test have been reported in the literature, ACI 544 [9] acknowledges that no standardized tensile testing procedure has been established specifically for FRC or ECC to accurately characterize the tensile response, particularly in the cases where strain-hardening behaviour and multiple cracking under tension are observed.

In a 2017 study published by Ali et al., the ultimate tensile strength of the ECC mixture containing 2% PVA fibers was 301.7% higher than that of the control mixture without fibers [10]. Similar results were obtained by Maalej et al. in a study that investigated the dynamic properties of ECC specimens, observing an increase in ultimate tensile strength of 190% with higher strain rates applied to the samples [11].

As an alternative to the direct uniaxial tensile test, indirect methods are recommended, in particular the splitting tensile test conducted in accordance with ASTM C496 or EN 12390-6. In this procedure, compressive load is applied to a cylindrical specimen along two diametrically opposed generating line, inducing a uniform tensile stress perpendicular to the line of loading which leads to failure of the specimen once the ultimate tensile strength is reached.

3.3. Beam flexural (bending) test

To address the inherent difficulties associated with performing direct tensile tests, several standards recommend flexural testing methods [9], specifically three-point or four-point bending. These are conducted in accordance with ASTM C293 or EN 12390-5 in the case of three-point bending. The testing method involves applying point loads to beam-sized specimens at prescribed locations, with the specimen typically supported in a simply supported configuration. During the test, both the first peak load and the residual load at specified deflections can be recorded, while simultaneously determining the modulus of rupture (MOR).

Several studies have reported that the incorporation of fibers leads to a significant enhancement in flexural strength, with FRC or ECC exhibiting improvements of 13% to 55% over plain concrete, depending on the fiber type, fiber volume fraction and mixture proportions [12]. One study reported that exposure to 500 °C resulted in a reduction of approximately 43% in the flexural strength of both ECC and PC specimens, a decrease more pronounced than that observed in compressive strength. This behaviour was attributed to the melting of PP fibers in the ECC matrix at approximately 180 °C and their subsequent evaporation at around 350 °C, which generated continuous voids within the microstructure and consequently weakened the material [13].

In a 2023 study, Guo et al. investigated the dynamic mechanical behaviour of ECC and found that increasing the fly ash (FA) content reduced the flexural peak load while increasing the flexural peak displacement. This behaviour was attributed to the ability of FA to lower the bonding force between the PVA fibers that were used and the matrix, thereby enhancing deformability [14].

3.4. Impact performance tests

In recent years, considerable research has been devoted to enhancing the understanding of the behaviour of ECC and FRC mixtures under various loading conditions. Particular attention has been directed toward impact loading, driven by recent global events (such as explosions, terrorist attacks, bombings and wars) and the consequent demand for construction materials with superior performance characteristics. It should be noted that, in the case of impact testing, the most commonly used standards are the ACI 544 [9] and the JSCE Concrete Engineering Series 82 [8], both of which provide guidelines for various types of testing procedures.

The multiple drop-weight test, either non-instrumented or instrumented, is the most widely employed method for evaluating impact performance. In the conventional non-instrumented drop-weight test, a weight is released from a predetermined height, and the number of impacts required to induce a defined level of distress is recorded. Although limited to qualitative assessment, the non-instrumented method enables comparative evaluation of different ECC specimens and provides a general indication of their impact resistance. In a study on the impact performance of self-compacting concrete reinforced with micro-steel fibers, it was observed that the specimen with 1% fiber volume required 672 blows from a 4.5 kg mass dropped at a height of 450 mm to initiate first cracking, while 789 blows were required to reach failure [15]. A similar high number of impacts was documented in another study on impact resistance that utilized two different types of fibers with varying volume fractions [12]. In instrumented impact testing, a specialized drop tower is typically employed, allowing sensors to capture parameters such as impact forces, displacements, and total energy absorption, thereby enabling a quantitative analysis of the results. A 2022 study on the low-energy impact behaviour of ECC and engineered geopolymer composite (EGC) reported dissipated energy values ranging from 2.1 J to 12.2 J, depending on drop height and mass [16]. Comparable results were documented in another study which reported a range of 10.3 J to 11 J on first impact and noted a nearly elastic response with no physical damage at lower energy levels [17].

During projectile testing, a projectile is launched toward a panel or comparable ECC specimens, and the dimensions of the resulting impact crater or scab are recorded. In the evaluation of concrete-based specimens, several challenges may arise, including the generation of dust that can hinder data acquisition of the impact event, as well as the ejection of debris from both the impact face and the rear face of the specimens. In a paper by Li et al., which addressed some of the shortcomings of projectile testing, it was concluded that coarse aggregate size has a greater influence on the impact resistance of the target than its hardness, thereby leading to the proposal of a new model for predicting the depth of penetration [18]. In another study on the impact resistance of ECC panels, Soe et al. reported that ECC panels absorbed nearly all of the impact energy compared to plain concrete, while exhibiting different failure modes depending on the number of impacts and the impact velocity [19]. These findings confirmed the results of an earlier study by Maalej et al. [11].

In certain studies, weighted pendulum tests are conducted using a conventional Charpy pendulum machine. The procedure consists of raising the pendulum to a predetermined height and subsequently releasing it to strike the test specimen. Upon impact, the specimen fractures and absorbs part of the pendulum’s energy. The residual energy enables the pendulum to ascend to a final height, from which the absorbed energy can be quantified. It should be emphasized that, a considerable portion of energy is dissipated during the test through friction and vibration. In a review study on the Charpy impact test applied to ECC, the authors concluded that several issues require further attention in the literature. These include specimen size and inconsistencies related to specimen dimensions, the advantages of using notched versus unnotched samples, and the detailed reporting of testing procedures, constituent materials and specimen characteristics [20]. The conventional testing machine may be instrumented with load cells, accelerometers and photocells to enable more precise measurements during the testing procedure.

Alternative impact tests may be performed using hydraulic universal testing machines, which are capable of inducing failure within short time intervals (on the order of 20 milliseconds), or by applying variable loading rates so as to generate distinct strain-rate conditions in the specimen.

4. Conclusions

Recent advancements in concrete research have led to the publication of numerous studies investigating fiber-reinforced mixtures and their potential integration into mainstream construction practices. To establish a robust understanding of the material's behaviour, various testing methodologies are employed to evaluate its mechanical properties and performance under diverse conditions. Nevertheless, notable discrepancies exist among testing procedures, standards used and other important criteria that may significantly influence the resulting data and interpretations. To facilitate further advancements in this field and promote the widespread adoption of fiber-reinforced concrete in practical applications, it is essential to develop and implement unified testing standards. Such standardization would provide the foundation for experimental evaluation and contribute to the subsequent formulation of comprehensive design guidelines.

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