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REVIEW

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Exploring Fracture Energy in Engineered Cementitious Composites: A Comprehensive Review

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Abstract

Engineered cementitious composites (ECC) boast superior tensile strain capacity and crack resistance compared to traditional concrete. A key contributor to this enhanced behavior is their high fracture energy, reflecting the material's ability to absorb energy before failure. This review paper comprehensively examines the factors influencing ECC fracture energy. It explores the impact of fiber properties (volume, type, aspect ratio), the binding matrix's characteristics, and the crucial fiber–matrix bond quality. The review dives deeper into established methods for measuring ECC fracture energy. It analyzes various test configurations and data analysis techniques used to quantify this vital property. Understanding how critical factors such as fiber volume, aspect ratio, and fiber type can improve or reduce the fracture process is discussed in this review. To optimize the ECC design, different experimental procedures along with their advantages and shortcomings and future testing methods to clearly evaluate the fracture behavior of ECC are discussed as well. This allows for achieving targeted fracture energy levels tailored to specific applications. Additionally, the review identifies promising directions for future research in ECC fracture energy. These include multi-scale modeling for enhanced design, exploration of advanced fiber engineering for improved performance, and the possibility of incorporating self-healing mechanisms for increased durability. Ultimately, this review aims to provide a comprehensive understanding of the factors governing fracture energy in ECC and the methods for its evaluation, paving the way for the development of next-generation ECC with superior functioning and broader applicability.

Keywords Fracture energy, ECC, Fracture mechanics, PVA fiber, PE fiber, PP fiber, Strain hardening, Strain softening

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1 Introduction

Engineered cementitious composites (ECC) are advanced cement-based materials reinforced with fibers, showcasing superior characteristics such as multiple cracking and tensile strain-hardening properties (Kanda, 2006; Li & Leung, 1992). Rather than relying on traditional trial-and-error methods, ECC is developed through micromechanical theory, achieving a tensile strain capacity exceeding 3% while utilizing a fiber content of no more than 2% (Li & Leung, 1992; Li & Wu, 1992; Li et al., 1995; Wu & Li, 1992). It is cement-based fiber-reinforced materials that demonstrate several cracking and tensile strain-hardening features. ECC is developed using micromechanical theory, as opposed to the conventional trial-and-error technique of material development, which yields a tensile strain capacity of more than 3% while maintaining a small percentage of fiber not more than 2%. ECC is a very durable material under environmental influences since it displays various cracking and strain-hardening behavior when subjected to tension, with a fracture width of less than 100 µm (Şahmaran, 2007). Table 1 delivers a concise overview of the main physical characteristics of ECC under static stress (Yu et al., Mar. 2018).

Earlier studies have been conducted on ECC design theory (Kanda et al., 2000; Li & Leung, 1992), mechanical properties (compressive, tensile, shear) and their models (Kanda et al., 2000; Lee et al., 2010; LIQinghua: The size effect of compressive properties of ultra hig... - Google Scholar, 2024) (Li et al., 2011a; Mechtcherine & Schulze, 2007), the impact of mineral admixtures, fracture behaviour (Li et al., 2011a; Mechtcherine & Schulze, 2007), durability, long-term tensile properties (Yang et al., 2009) (Kan et al., 2010), self-healing mechanisms (Kan et al., 2010; Li et al., 1998; Qian et al., 2009; Wu et al., 2012; Yang et al., 2009), nanoscale structure (Sakulich et al., 2011), crack propagation simulations (Huang et al., 2016a, 2016b), and reinforced member applications (Rokugo et al., 2013), has further enhanced the adaptability of ECC material. Beyond the US, other nations that have successfully made ECC utilizing indigenous material ingredients include South Africa (Boshoff, 2007), China (Ma et al., 2015; Pan et al., 2015; Zhang et al., 2014), Europe (Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC) 2011; Mechtcherine & Schulze, 2007), and Japan (Kanda, 2006). It is noted that several real-world applications have already been implemented in the US, China (Zhang et al., 2013), and other countries. Over the last 20 years, several evaluations have been done on ECC (Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC)2011), examining its endurance in different settings (Rokugo et al., 2013), examining its structural design and performance, and (Wu et al., 2012) examining its self-healing capabilities.

Fracture energy(G_f), is the quantity of energy absorbed to produce a unit area of a fracture, is a crucial statistic for describing the capacity of concrete material to dissipate energy. It is well known that incorporating fibers into cementitious materials is capable of improving their fracture energy. Several factors influence the fracture energy of cementitious materials, including the size and shape of coarse aggregates, the internal structure of the paste matrix, the bonding regions between aggregates and paste (ITZs), and the properties of any embedded fibers (Bosque et al., 2017; Ding et al., 2018; Wang et al., 2009; Zegardło et al., 2016). For quasi-brittle cementitious materials, including normal concrete and most fiber-reinforced concrete, that show tension-softening behavior, just one fracture appears across the specimen. The fracture energy of an FRC material may be estimated directly by computing the area contained by the full load–displacement curve acquired using different methods like as four-point bending testing, wedge splitting testing, direct tension testing, and so on. Despite being much bigger than that of normal concrete (i.e., less than 0.2 kJ/m^2) (Landis, 2002; P. P.-C. & C. research & undefined, 1980; Wittmann et al., 1990; Yu & Lu, 2014; Yu et al., 2012, 2015, 2016), the fracture energy of FRC is less than 10 kJ/m^2 (Akcay et al., 2012; Banthia 2003a; Barros & Cruz 2001), and so on. Closely spaced cracks develop in strain-hardening cementitious composites, like ECC, when they are exposed to tensile or flexural stresses. A typical load–displacement curve can reflect both a protracted tension-hardening branch and a strong post-peak tension-softening behavior.

The fracture energy of ECC plays a critical role in finite element method (FEM) modeling and civil engineering applications. ECCs are engineered to demonstrate exceptional mechanical properties, like high ductility and improved fracture toughness, which are critical for forecasting structural behaviour under different loading conditions.

Table 1 Main physical characteristics of ECC (Yu et al., 2018)

f'_c(MPa)	First cracking strength (MPa)	f_t(MPa)	ε_u^t(%)	E(GPa)	σ(MPa)	ρ(g/ml)
20–150	3–10	4–20	3–12	18–40	10–50	0.95–2.3

$f_c\prime$, f_t are the compressive and ultimate tensile strength, ε_u^t is the ultimate tensile strain, E and σ are the modulus of elasticity and flexural strength, respectively, and ρ is the density

Fracture energy measures the energy needed to produce a new surface in a material, which becomes very meaningful in the context of ECC due to its pseudo strain-hardening property. This attribute enables ECC to get fractured multiple times, which can help in dissipating the energy and improving the force of the material (Baloch et al., 2022; Gupta et al., 2024). As reported by Gupta, ECCs showed a fracture toughness of 73.68 ± 8.02 MPa.mm^2, significantly more than conventional concrete (Gupta et al., 2024).

Because it affects the material's response to stress and its capacity to tolerate dynamic loads, like those encountered during seismic occurrences, high fracture toughness is essential for FEM modeling (Basha et al., 2021; Yuan et al., 2017). It has been demonstrated that the use of ECC in civil engineering greatly enhances performance, especially in seismically active areas. According to studies, ECC can increase structural elements' ability to dissipate energy, improving their ductility and minimizing damage during earthquakes (Basha et al., 2021; Xu et al., 2018). Designing resilient structures requires more accurate predictions in FEM simulations, which are made possible by ECC's capacity to regulate crack width and distribute stress through a variety of cracking mechanisms (Yuan et al., 2017; Zhang et al., 2016).

Additionally, adding PVA fiber to ECC increases its overall mechanical performance and fracture energy. Studies have revealed that the incorporation of fibers improves tensile strength and ductility, which are crucial parameters in modeling structures (Sun, et al., 2018; Zhang et al., 2016). ECC's fracture characteristics, such as its capacity to absorb energy, are essential for making sure that structures can sustain unforeseen loads without failing catastrophically (Li & Xu Jun., 2011; Pakravan et al., 2016).

To put it briefly, the fracture energy of ECC is a basic characteristic that has a big influence on FEM modeling and applications in civil engineering. ECC is an excellent option for boosting the resilience and endurance of structures, especially in seismic zones, due to its high energy dissipation and fracture toughness.

It is notable that understanding of fracture energy of ECC had been performed on minimal scale. Therefore, it is necessary to further investigate that how fracture energy varies under ECC and its components. This bibliographic and critical analysis study aims to assess the variables influencing ECC's fracture energy and the techniques employed to determine the ECC's fracture energy.

2 Research Methodology

The research approach utilized to carry out this comprehensive review is shown in the flowchart in Fig. 1, and it comprises the following three main steps:

Step 1: Database and keywords selection.

The two most popular databases, Web of Science (WoS) and Scopus, are the foundation for this review study. Following the search databases' selection, appropriate keywords need to be identified. The most frequently used keywords associated with ECC fracture energy were utilized to get a more extensive collection of bibliometric information. "Fracture Energy" or "Fracture Mechanics" and "ECC" or "Engineered Cementitious Composites" are the search terms that were utilized. After completing this step, 42 earlier items were acquired.

Step 2: Articles list selection.

Four steps were performed to reduce the number of studies (42 articles) and retain just the relevant ones:

- Criteria for inclusion and exclusion: All research about fracture energy of ECC has been included. On the other hand, those that were published in languages other than English were disregarded. There were 39 articles in total from the numbers of the previous articles.
- Evaluation of publications based on screening titles and abstracts: 2 articles were eliminated, leaving 37 remaining after screening titles and abstracts.
- Full-text evaluation: 37 articles were produced after eliminating based on the full-text evaluation.
- Snowballing search: To locate more papers that Scopus or WoS did not discover, the reverse snowballing technique was employed. 21 additional relevant articles were found using this search approach, increasing the total number of connected studies to 58 (37 + 21).

Step 3: Scientometric and systematic review.

This review includes the scientometric and systematic analysis, conducted using the entire number of relevant papers (58). As shown in Fig. 1, the scientometric and systematic reviews have both been achieved in the subsequent parts.

3 Scientometric Analysis

3.1 Annual Publications Trend

A review of publications published between 2000 and 2023 indicates a significant increase in research efforts in ECC fracture mechanics. Even with its limits (focused on the years 2000–2023, with the first publication detected in 2005; refer to Fig. 2), the bibliometric data collection nonetheless shows a distinct pattern. The increasing volume of published works, especially from 2009 to 2021 (Fig. 3), attests to the expanding significance of this field of study. This pattern points to the need for a global effort to comprehend ECC's energy dissipation properties and fracture behavior.

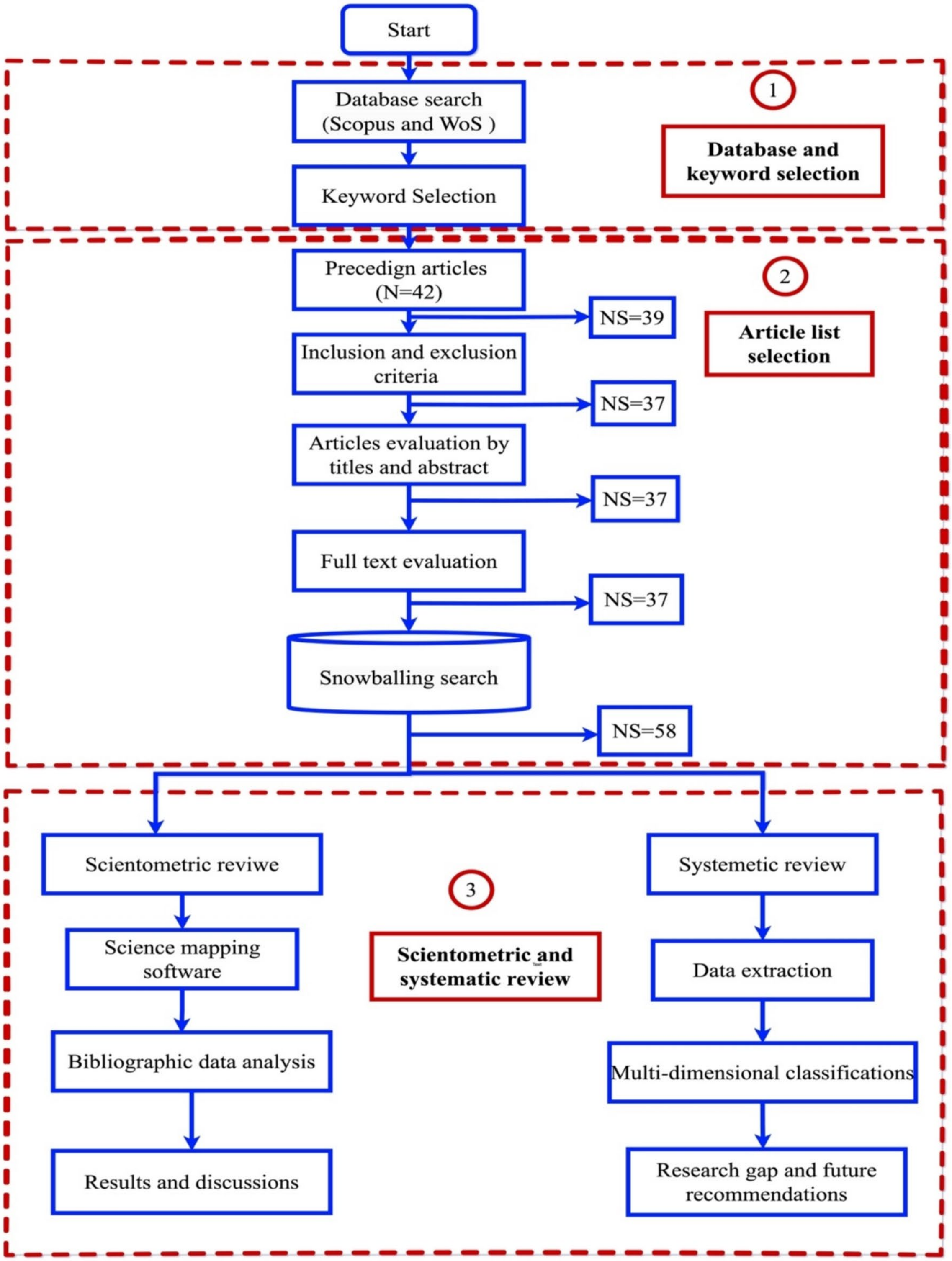

Fig. 1 Flowchart methodology for the study

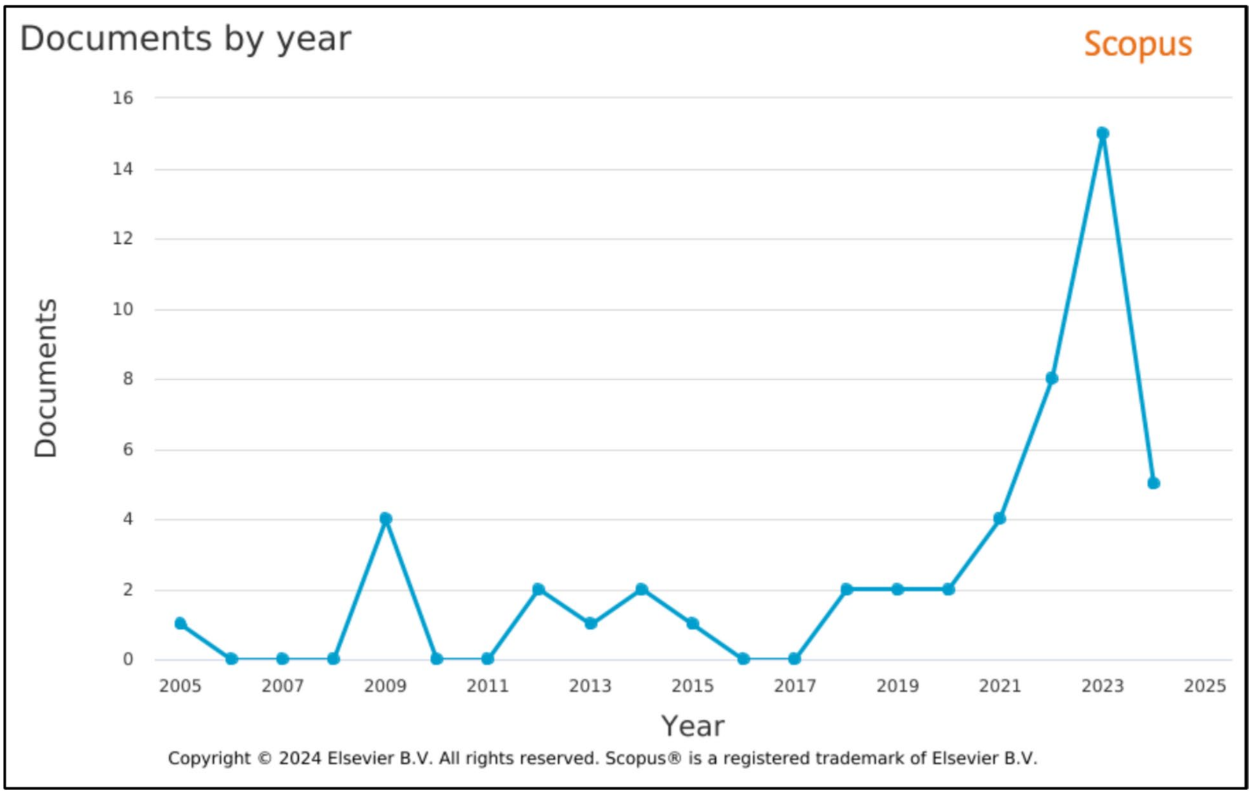

Fig. 2 A visual representation of frequently appearing top 20 terms across the 58 articles

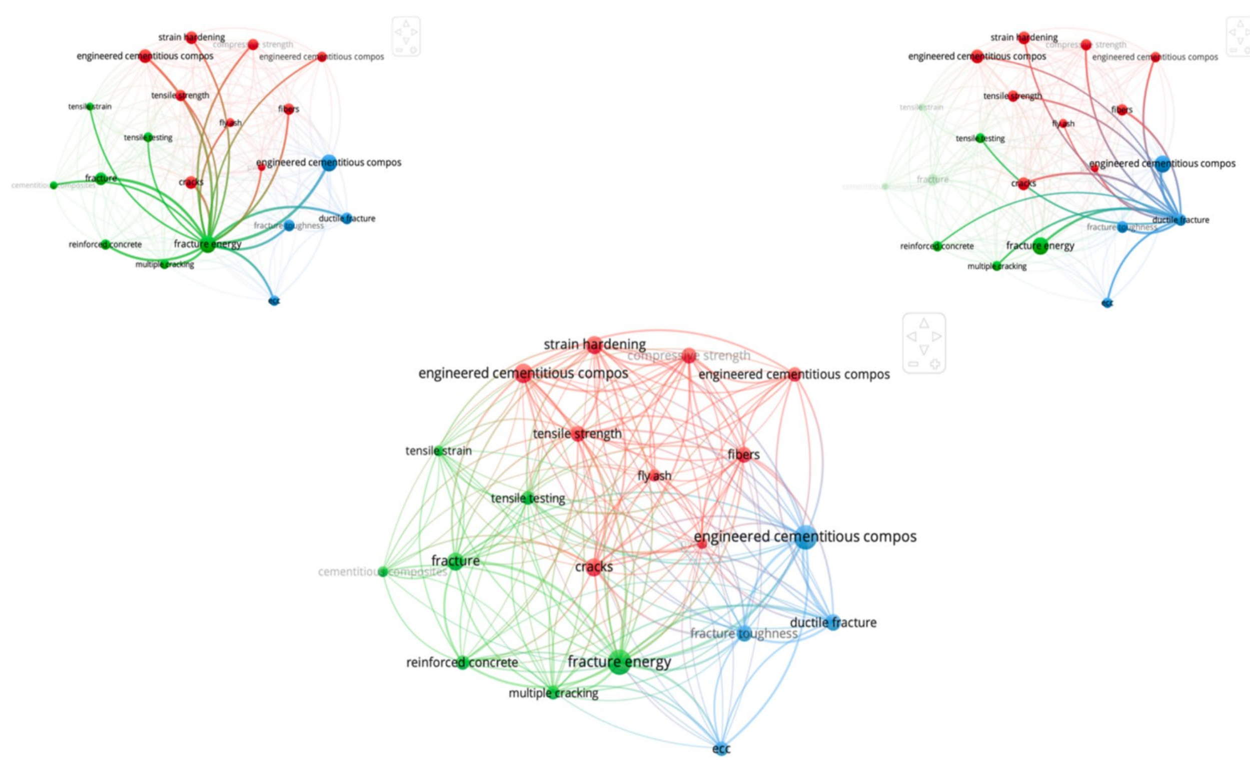

Fig. 3 Annual trend of the studies conducted on fracture energy of ECC

4 Keywords Co-occurrence Network

Without diving too far into the publications, the keywords are crucial since they represent the tone and content of the published pieces. As a result, mapping the keywords of pertinent papers within a certain field of study might reveal the gaps and approaches that have been employed in that field. Using keywords from the 58 articles, a co-occurrence network visualization was made in VOSviewer to examine the connections between terms that appeared frequently. Of the 555 keywords, 20 had the required number of occurrences, or 5. For each of the 20 keywords, the overall strength of the co-occurrence with other terms has been computed using the VOSviewer program. Fig. 2 shows the 20 keywords for the 58 relevant articles as a co-occurrence network visualization. The label's size and the circle surrounding it are determined by the weight of each keyword. The latter expands in size in proportion to the weight of the keyword. For instance, due to their high frequency of occurrence, the fracture energy and ECC keywords have the largest label and circle size. Table 2 reports the top 20 active keywords in the fracture energy research field based on total link strength and occurrences.

Table 2 Top keywords in the field of fracture energy of ECC

No	Keywords	Occurrences	Total links
1	Cementitious composites	5	19
2	Compressive strength	9	57
3	Cracks	11	59
4	Ductile fracture	10	55
5	ECC	8	34
6	ECC	8	36
7	ECC	13	53
8	ECC	18	81
9	Fibers	9	53
10	Fly ash	6	33
11	Fracture	11	54
12	Fracture energy	19	89
13	Fracture toughness	10	51
14	Multiple cracking	7	40
15	pva fiber	5	37
16	Reinforced concrete	8	38
17	Strain hardening	11	57
18	Tensile strain	5	26
19	Tensile strength	9	49
20	Tensile testing	7	39

4.1 Prominent and Active Countries in This Research Area

The determination of the main nations engaged in the ECC study on fracture behavior is to share information and work together in the future. Fig. 4 lists the leading nations in this field of study. Scopus data from 2000 to 2023 were used to construct this graph. China, and the United Kingdom, for instance, have bigger labels than the other nations. However, the 42 publications that were

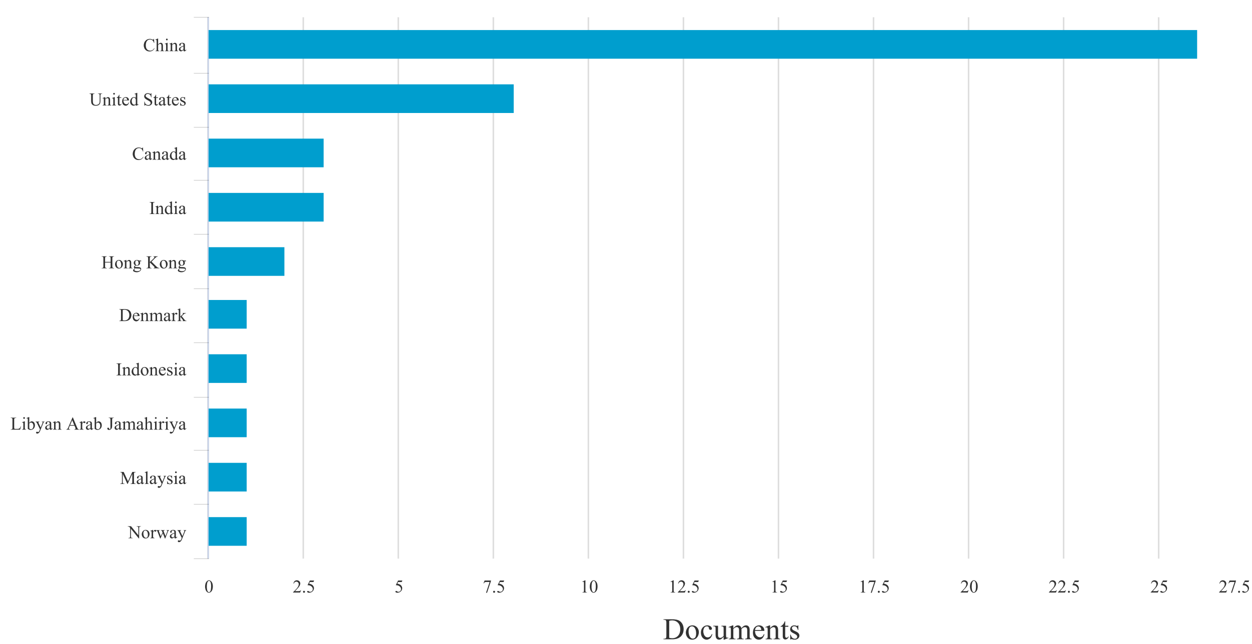

Fig. 4 Total number of publications by country

retrieved and examined indicate that these nations contribute the most to this field of study.

5 Methods to Determine Fracture Energy

The amount of energy required to produce a single crack is defined as fracture energy. Equation (1) can be used to compute fracture energy:

$$G_f = \frac{W}{A} = \frac{\int F(\delta)d\delta}{A}. \tag{1}$$

W represents the amount of work required to create a unit crack, A represents the ligament area and represents the crack opening.

Wille (Wille & A., 2010a) split the G_f of ECC into strain-hardening energy ($G_{f,H}$) energy and strain softening ($G_{f,S}$) energy, as illustrated in Fig. 5. Furthermore, the G_f can be determined using Eqs. (2), (3), (4), (5), (6):

$$g_{f,H} = \int_{\varepsilon=0}^{\varepsilon=\varepsilon} \sigma c(\varepsilon)d\varepsilon - \frac{1}{2}\frac{\sigma_{pc}^2}{E_{pc}}, \tag{2}$$

$$G_{f,H} = g_{f,A} \times \frac{L_g}{n_{cr}} = \frac{G_{f,H,n}}{n_{cr}}, \tag{3}$$

$$G_{f,S} = \int_{\delta=\delta_{pc}}^{\delta=\delta_u} \sigma(\delta)d\delta, \tag{4}$$

$$\delta_{pc} = \varepsilon_{res} \times s_{cr} = \left(\varepsilon_{pc} - \frac{\sigma_{pc}}{E_{pc}}\right) \times \frac{L_g}{n_{cr}}, \tag{5}$$

$$G_f = G_{f,H} + G_{f,S}. \tag{6}$$

Note: $G_{f,H,n}$ is the total energy required to produce n_{cr} cracks with a permanent δ_{pc}, δ_{pc} is a permanent crack opening, ε_{res} is the residual strain, $\delta_u = L_p/2$ is the ultimate crack opening, and L_p is the fiber length. Additionally, σ_{pc} and ε_{pc} represent peak stress and peak strain, E_{pc} is the modulus during unloading, L_g is the uniaxial tensile test specimen gauge's length, n_{cr} is the number of cracks generated within L_g, s_{cr} is the average crack spacing. It is assumed that n_{cr} microcracks are uniformly distributed and formed within the L_g range when computing $G_{f,H,n}$. Furthermore, the energy of each ligament area dividing the major crack from to δ_u is indicated by $G_{f,S}$. It is evident from Fig. 5 and Eqs. (2)–(6) that G_f computation requires the presence of E_{pc}.

Japan Concrete Institute (JCI) (Kitsutaka et al., 2001) and RILEM (Partha Uday 2017) have standardized a three-point bending test to measure the fracture energy of concrete. However, there is no standard method for measuring the fracture energy of ECC materials. Different authors have adopted different methods to measure the fracture energy of ECC materials. Dog bone shape samples are considered for the direct tension test of fibrous materials researchers (Yu et al., 2020; Zhu et al., 2023) have also used this method to detect the fracture energy of ECC material. Similarly, some authors have considered the JCI and RILEM recommended three-point bending test method on a notched specimen to measure the fracture energy of ECC (Gao et al., 2022, 2023). Other researchers have also considered wedge-splitting sample (Gao et al., 2012), four-point bending (Tan et al., 2022), and single shear test (Shiping et al., 2022) methods to observe the fracture behavior of ECCs. Table 3 provides the details of the method used to study the fracture energy of ECCs. Fig. 2 shows the trends of research done on fracture energy of ECC from Scopus data set.

5.1 Effect of Fibers

The performance of ECCs with different polymeric fibers was found to be highly influenced by the type and volume of fibers, with polyvinyl alcohol (PVA) fibers demonstrating superior performance in terms of the stress–strain

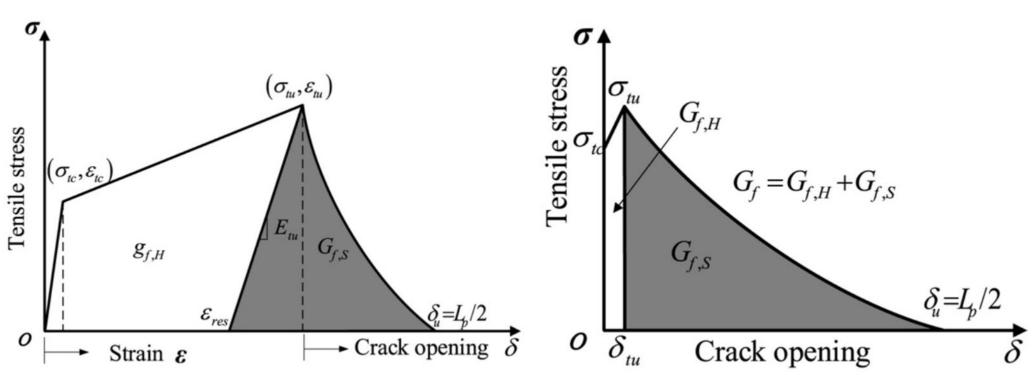

Fig. 5 Explanation under tension test. a G_f per unit area, b G_f related to failure causing cracks

Table 3 Details on the type of sample, fiber type, and parameters studied for the fracture energy of ECCs

Year	Sr. #	Method	Fiber	Parameters	Refs.
2023	1	Dog bone shape	PE	w/c ratio, fiber vol, and fiber aspect ratio	Zhu et al., 2023
2023	2	Double-notched and unnotched	PVA	Notch depth	Gao et al., 2023
2022	3	Three-point bending	PVA	Notch depth	Gao et al., 2022
2023	4	Dog bone and notched beam	PE	w/c ratio	Ding & Tao Yu et al., 2018
2020	5	Dog bone shape	PE	Fiber vol., aspect ratio	Yu et al., 2020
2023	6	Wedge splitting sample	PE	Variable temperature	Shang et al., 2023
2023	7	Flexural test	Carbon Fibers	Virgin carbon fibers and recycled carbon fibers	Al Moman et al., 2023
2003	8	Contoured double-cantilever beam	Steel and polypropylene	Fiber type	Banthia 2003a
2023	9	Notch beam	PVA	Fiber surface	Guan et al., 2023
2023	10	Notch beam	PVA	Immersion time and temperature	Gao & Xie, 2022a
2023	11	Notch beam	PVA	Loading rate	Gao et al., 2023; Ruiz et al., 2011
2023	12	Dog bone	PVA	w/c, fiber vol	Zhao et al., 2022
2022	13	Notch beam	PVA	Temp and duration of moisture	Gao et al., 2023
2022	14	Four-point bending	PP	Fiber vol	Tan et al., 2022
2022	15	Single shear test	PVA	Basalt–glass mixed textile, etc	Shiping et al., 2022
2022	16	Single shear test	PVA	Freeze–thaw cycle	Gao & Xie, 2022a
2012	17	Wedge splitting sample	Glass, PVA, and steel	Fiber type	Gao et al., 2012
2011	18	Dog bone	PVA	w/b and POFA	Johari et al., 2015

and load–displacement behavior relationship (Gao et al., 2012). Better flexural and tensile strength indicate that increasing ECC's fiber capacity improves tensile behavior. Higher fiber volume fractions typically result in improved mechanical characteristics, like increased tensile strength and strain-hardening characteristics. Fiber volume has a considerable impact on the tensile behavior of designed cement-based composites. Similarly, this section discusses the impact of fiber type, fiber volume, and fiber aspect ratio on the fracture energy of ECCs. Table 3 gives the details of the specimen, type of fiber, and factors considered for the fracture energy of ECC materials.

5.2 Effect of Fiber Type

Double-cantilever beam (DCB) experiments were used by Tan et al., 2022 to look into the impact of polyethylene (PE) fiber volume percentage (0.2–4%) on the fracture energy of PE-ECC. The total fracture energy (G_f) was calculated by adding the fracture energy generated by crack localization in the post-peak section ($G_{f,S}$) to the fracture energy produced by many cracking processes in the pre-peak section ($G_{f,H}$). On 2% fiber composites, the G_f observed was approximately 26.9 kJ/m^2, while the fracture energy generated by crack $\left(G_{f,S}\right)$ localization was approximately 12.2 kJ/m^2. With 2% PVA fiber, the G_f of ECC with PVA fibers measured by earlier researchers by the uniaxial tension test (Shiping et al., 2022; Gao et al., 2023) ranged from 5.54 to 6.69 kJ/m^2. The G_f of steel and polypropylene fiber-reinforced hybrid SHCC ranged from 2.2 to 4.5 kJ/m^2 (Ding & Tao Yu et al., 2018). UHPC may demonstrate extraordinarily high G_f of not less than 30 kJ/m^2 by adding a low volume fraction of 2% of deformed steel fiber (Shang et al.,2023). According to the definition, the fracture energy of SHCC should only contain the energy released by a single crack during strain-hardening and softening branches (Shang et al.,2023). This ignores the energy dispersed by multiple crack origination during the process of strain-hardening and is unable to fully reflect the crack resistance capacity of SHCC. The fracture values of steel fibers were significant when compared with PP fibers. It was also noticed that secondary fibers enhanced the fracture energy and crack formation pattern (Ding & Tao Yu et al., 2018). In addition, the G_f of the combined PVA and glass fibers was lower than the fracture energy of the sample containing only 1% of PVA fibers. The specimen containing 2% of PVA fibers had less G_f than 1.5% of PVA fibers and more than 1% of PVA fibers in the mixture. It was also observed that adding more glass fiber did not increase the matrix's toughness. The G_f of PVA fibers with extra glass fibers is only 1/3 of 1% PVA fiber when only 0.96% glass fiber is added (Gao et al., 2012). This demonstrates in full the benefit of PVA fiber in cementitious composites toughening. The nominal fracture energy (G_f) index can be utilized to assess the toughness of strain-softening materials. PVA fiber can modify the geometry of cracks at the precut crack tip in addition to significantly raising the nominal G_f of cementitious composites. Strain-softening composites have only one primary fracture that extends along the precut crack tip. However, the major crack does not always occur along the precut crack tip; instead, several microcracks form around the crack point, much like an onion. Studies have demonstrated that PVA fiber has the greatest toughening impact on cementitious composites. Furthermore, steel fiber-reinforced concrete and ECC have the same nominal fracture energy. Steel fiber applied to mortar has less toughness than steel fiber added to concrete. Glass fiber composites are not as tough as steel fiber composites. The relatively best toughening material is PVA fiber rather than glass and steel fibers(Gao et al., 2012).

5.3 Effect of Fiber Volume

Research on the impact of fiber volume on the fracture energy of engineered cementitious composites (ECC) is crucial since it directly affects the materials' durability and mechanical performance. Fiber addition greatly improves the strain-hardening characteristic that ECCs are intended to display. Fracture energy, a measurement of a material's capacity to absorb energy during fracture, is mostly determined by the volume fraction of fibers. When the fiber volume rises, ECC's fracture energy also increases dramatically. In particular, $G_{f,H}$, $G_{f,S}$, and G_f rose by 89.51%, 64.01%, and 64.67%, respectively, when fiber volume increased from 1.4% to 2.0% (Zhu et al., 2023). This behavior is largely produced by a greater fiber volume percentage, which increases the quantity of fibers in the cementitious matrix as well as the amount of bridging fibers at the fractures. This improves the ECC's capacity to resist breaking and disperse energy, hence raising the fracture energy. As the volume percentage of PVA fiber grew (1.0%, 1.5%, and 2%), fracture energy increased by 47.8% and 114%, respectively. This implies that adding PVA fiber to an ECC at a concentration of 1.0% to 1.5% can improve its G_f. This may be due to the fact that the extra fiber increases the bridging action between the cementitious matrix and the fibers at the crack, allowing for the dissipation of more energy from cracking to fracture (Al Moman et al., 2023).

Studies show that a growth in the content of fiber typically results in an increase in fracture energy. For example, Kim et al. showed that the highest flexural strength of 45 MPa was achieved with a fiber volume fraction of 6% (Kim et al., 2020), suggesting that increased fiber content enhances toughness and resistance to brittle failure. The inclusion of PVA fibers enhances ductility and fracture toughness, and the rise in fracture toughness is shown to be linear with increasing fiber volume percentage, according to Xu et al. (2011).

The ability of the fibers to redistribute stress and bridge cracks is the mechanism responsible for the increase in fracture energy with fiber volume. When fibers are introduced, the composite's behavior changes from brittle to ductile by improving its ductility and slowing the spread of cracks. Because the increased fracture energy might prevent catastrophic failures, this is especially crucial in applications where ECCs are subjected to dynamic loads or impacts (Etminani & Sharif 2018).

Additionally, the way the fibers are distributed inside the composite matrix is quite important. Processing methods have a major impact on fiber distribution, which in turn affects the mechanical performance of ECCs, according to Niu et al. (2013). A well-distributed fiber network maximizes the effectiveness of the fibers in resisting fracture, thereby enhancing the overall fracture energy of the composite.

5.4 Effect of Fiber Aspect Ratio

The increase in $G_{f,H}$, $G_{f,S}$, and G_f was observed with an increase in the fiber aspect ratio. In particular, $G_{f,H}$, $G_{f,S}$, and G_f rose by 117.58%, 13.19%, and 16.42%, respectively, when the aspect ratio increased from 480 to 818. This trend can be justified by the fact that a fiber with a larger aspect ratio has a more effective bond area with the matrix, which increases the energy dissipated by the fiber pullout during matrix cracking, leading to a higher fracture energy (Zhu et al., 2023). G_f generally increased as the $\frac{V_f L_f}{d_f}$ value increased. The G_f of PE-ECC increased steadily for the instance of water-to-binder ratio of 0.16, rising from 10.08 kJ/m^2 to 16.04 kJ/m^2 which is an increment of 58.9% as the $\frac{V_f L_f}{d_f}$ value increased from 5 to 18 (Yu et al., 2020). Likewise, a similar tendency was seen in the association between $\frac{V_f L_f}{d_f}$ and the PE-ECC fracture energy at various w/b ratios. The concept of $\frac{V_f L_f}{d_f}$ is linked to the probability of fibers being present at the critical crack surface, a factor heavily influencing the energy dissipation capacity of the composite material. A higher $\frac{V_f L_f}{d_f}$ value suggests more fibers bridging the crack due to a larger effective area for fiber–matrix bonding across the crack section. This translates to greater energy consumption during the fiber pull-out process, ultimately resulting in higher fracture energy G_f as illustrated in Fig. 6. The graph reveals a fascinating interplay between fiber aspect ratio and different energy components in the material. While the total fracture energy remains remarkably stable at around 7 kJ/m^2 across all fiber aspect ratios (500–900), the internal energy distribution shows distinct patterns. The softening energy demonstrates a clear positive linear trend, increasing significantly with higher aspect ratios, suggesting that longer fibers contribute more to the material's post-peak energy absorption capacity. In contrast, the hardening energy remains

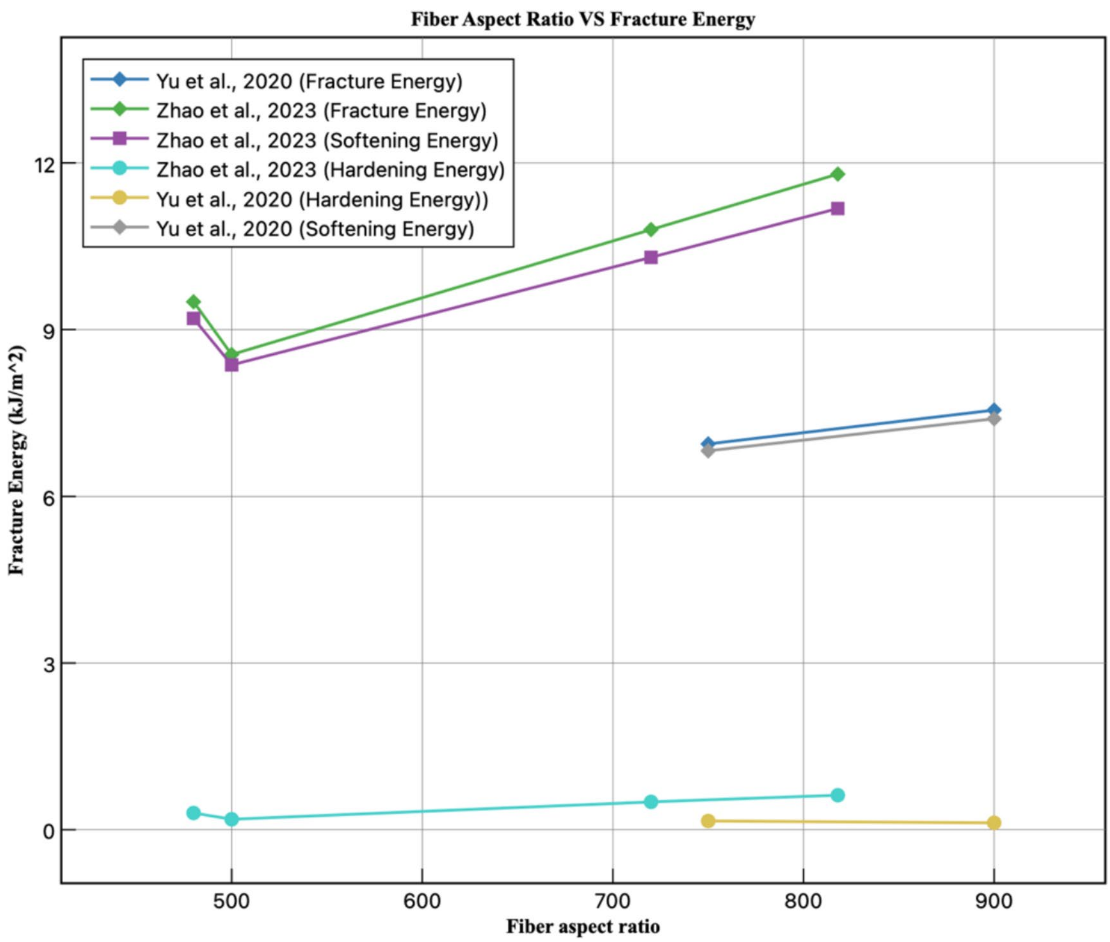

Fig. 6 $G_{f,H}$, $G_{f,S}$, and G_f variation concerning the aspect ratio of fibers

consistently minimal (near 1 kJ/m^2) regardless of aspect ratio changes. This pattern, validated by independent studies indicates that while fiber aspect ratio significantly influences the material's post-peak behavior through enhanced softening energy, it has minimal impact on the overall fracture energy and hardening characteristics.

The aspect ratio of fibers used in engineered cementitious composites (ECC) significantly influences their mechanical behavior, particularly in terms of strain hardening and strain softening. Strain hardening is characterized by an increase in stress with increasing strain, leading to multiple cracking and enhanced ductility, while strain softening refers to a decrease in stress after reaching a peak load, resulting in reduced load-bearing capacity. The fiber bridging mechanism in ECC is the prime reason for strain-hardening behavior in the ECC matrix. The fiber bridge prevents the expansion of cracks, ultimately allowing the material to withstand significant deformation before failure.

Fiber aspect ratio plays an important role in determining the tensile strength and strain capacity of ECC. Zhou et al. compared the PE fibers and steel fibers and reported that PE fibers with a high aspect ratio (750) led to a tensile strength of approximately 15.5 MPa and a maximum tensile strain capacity of 9%, while steel fibers with a lower aspect ratio (65) exhibited strain-softening behavior with a tensile strength of only 8.5 MPa (Zhou et al., 2018). These differences demonstrate the significance of fiber geometry in improving ECC mechanical properties.

Other studies validated these findings showing that there is an optimum aspect ratio of fibers for obtaining maximum performance. In a study, Wnag et al. compared the different aspect ratios (55, 65 and 80) of steel fibers and concluded that 65 was the optimal aspect ratio for steel fibers in ECC yielding higher compressive strength (Su & Cai, 2013).

Fiber distribution also affect the strain-hardening behavior of ECC. A poor fiber distribution causes adverse effect on strain hardening as stated by Niu et al. (2013) due to the localized weakness in the composite. This is supported by Yang and Li, who reported that fiber distribution and fiber content directly impacted the tensile strength and strain capacity of ECC (Yang & Li, 2016). Furthermore, Zhang et al. emphasized that the geometry and aspect ratio of fibers are pivotal in determining the overall performance of ECC, as they affect the material's ability to undergo multiple cracking and maintain ductility under load (Zhang et al., 2018).

In brief, the fiber aspect ratio is a key factor influencing the strain-hardening and softening behavior of ECC. Higher aspect ratios tend to improve tensile strength and strain capacity, while optimal fiber distribution and effective fiber/matrix bonding further contribute to the material's overall performance. Results from various studies highlight that fiber properties must be carefully considered in the design of ECC to achieve the desired mechanical properties. Table 4 provides a summary of the effect of fibers on the strain-hardening and strain-softening behavior of ECC.

5.5 Effect of w/c Ratio

The $G_{f,H}$ is 0.38 kJ/m^2, $G_{f,S}$ 1.66 kJ/m^2, and G_f 12.04 kJ/m^2 when w/b equals 0.21. As a result, the strain-softening phase of ECC has a fracture energy that is significantly higher than the strain-hardening phase. Furthermore, the ECC fracture energy dramatically dropped as w/b increased. $G_{f,H}$, $G_{f,S}$, and G_f dropped by 25.72%, 44.23%, and 43.64%, respectively, when water-to-binder ratio increased from 0.21 to 0.30 (Zhu et al., 2023). This is mostly because, a lower ratio of w/b corresponds to a higher interfacial friction force between the matrix and the fiber as well as a more energy consumption during the pulling out of the fiber, which raises the fracture energy. In a study it was revealed that, except a specific case (w/c, w/b, of 0.14), fracture energy of PE-ECC generally reduced with growing w/b ratios. This trend held true regardless of the VfLf/df values (fiber volume and aspect ratio product). As shown in Fig. 7a a decrease in w/b from 0.32 to 0.16 led to a significant increase in

Table 4 Strain Hardening and Strain Softening behaviour of ECC blended with various types of fibers

Aspect	Strain hardening	Strain softening
Fiber bridging	Effective bridging across cracks (Cao et al., 2015; Lan et al., 2021; Mechtcherine et al., 2005)	Ineffective bridging due to high matrix strength (Noorvand et al., 2019)
Fiber types	PVA, PP, PE, steel	PVA (with improper reinforcing index)
Hybrid fibers	Enhanced strength and ductility (steel + PP) (Banthia, 2003b; Wille, 2010b)	Not typically used for strain-softening
Fiber content	Effective at low content (1.5%) (Mechtcherine et al., 2011a)	High matrix strength leading to softening (Noorvand et al., 2019)
Fiber–matrix interface	Strong bond necessary for hardening (Mechtcherine et al., 2011a)	Weak bond leading to fiber pull-out (Mechtcherine et al., 2011a)

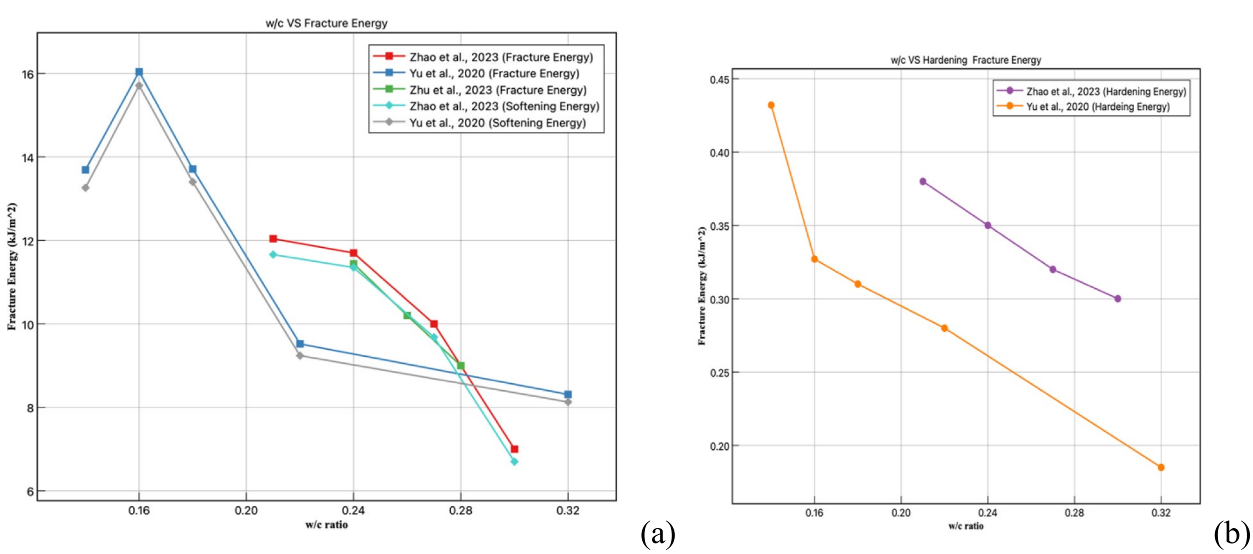

Fig. 7 W/c ratio effect on fracture energy of ECCs, **a** $G_{f,S}$ and G_f variation w.r.t w/c, **b** $G_{f,H}$ variation with w/c (Al Moman et al., 2023; Li & Xu Jun., 2011; Sun, et al., 2018).

fracture energy, from 8.70 kJ/m^2 to 15.5 kJ/m^2 (representing a 76.79% improvement). This coincided with a rise in compressive strength from 43.0 MPa to 94 MPa for $*=$ 15 (an increase of 118%). However, when the w/b ratio further increased to 0.14, the fracture energy dropped to 12.57 kJ/m^2 despite a higher compressive strength of 115 Mpa (Yu et al., 2020). Fig. 7b demonstrates a clear inverse relationship between the w/c ratio and the hardening fracture energy in ECC materials. As the w/c ratio increases, studies show a consistent decrease in fracture energy, though Zhao et al.'s results maintain higher absolute values throughout compared to Yu et al.'s findings. This trend suggests that higher water content relative to cement leads to reduced fracture resistance in the material, with Zhao et al.'s study showing a more gradual decline compared to the steeper drop observed in Yu et al.'s data, though both ultimately confirm that lower w/c ratios result in stronger, more fracture-resistant cement compositions.

The non-homogeneous cementitious matrix and the interfacial tension zones (ITZs) between the PE fibers and the PE-ECC matrix are where the first microcracks were found. As a result, PE-ECC's improved strength led to a higher packing density between the ITZs and cementitious matrix, which may have a positive effect on PE-ECC's fracture energy and reduce the beginning of cracks. Furthermore, when the external stress increased, many fibers were ripped out of the matrix as cracks developed and spread throughout the ITZs and matrix between the PE fibers. As a result, greater energy dissipation, during the pull-out process of fiber, and improved fracture energy would result from stronger matrix/fiber interface friction strength brought on by the lowering of the w/b ratio. However, the extremely low w/c ratio (i.e., 0.14) may introduce a friction strength at the fiber/matrix interface that is greater than the PE fiber's tensile strength, resulting in more fiber rupture failure than fiber pullout (Guan et al., 2023), which has a detrimental effect on the fracture energy. Unlike PE-ECC, where fracture energy declines with increasing water–binder ratio, PVA-ECC shows an increase in energy dissipation capability. With the increase in w/b ratio from 0.24 to 0.28, the fracture energy of PVA-ECC strengthened by 26.9% and 18.4%, respectively (Al Moman et al., 2023). This suggests that a lower water–binder ratio in PVA-ECC reduces its ability to disperse energy.

5.6 Effect of Loading Rate

The mode I fracture test of steel fiber-reinforced concrete was carried out by Zhang et al. (2018) at stress rates between 10^3 mm.s^{-1} and 10^{-3} mm.s^{-1}. The fracture energy and peak load dynamic increase factors were around 2.5 and 3.5, respectively, at the fastest loading rate of 10^3 mm/s. Using the semicircular bending test method, Ruiz et al., 2011 investigated the effects of 5, 1, and 0.5 mm.min^{-1} loading rates on the mode I G_f of high-strength FRC, which includes glass, polypropylene, and steel fiber. Steel fiber-reinforced concrete showed the greatest sensitivity to loading rates among them. According to Zhang et al. (2013), the loading rate within the range of 10 to 10^{-4} mm.s^{-1} increased the peak load and G_f of high-strength concrete. However, the growing amplitude was very little, which can be described by the viscous impact of the water in the pores of composite structure. In contrast, the influence of inertia caused the peak load and G_f to increase notably in the range of 10^3–10^2 mm.s^{-1} loading rate. Zhang et al. (2010) investigated how loading rate affected the spread of cracks in high-strength concrete. At lower loading rates of 5.4×10^{-4} mm/s–17.3 mm/s, the low loading rate significantly affected the crack growth rate; and at high loading rates (8.8×10^2 mm.s^{-1} – 2.64×10^3 mm.s^{-1}), there was no significant effect on the fracture propagation rate. The addition of fiber at varying loading rates will alter the crack growth law and complicate mixed mode I–II fractures as the fiber's bridging performance increases the toughness of concrete (Gao et al., 2023). Shear cracks developed in the specimen after tensile cracks, according to Arslan's (1995) observation. Concrete can be made more impact-resistant by adding fiber reinforcement, and under impact loads, fiber-reinforced concrete has a larger fracture energy than regular concrete. According to research by Boshoff and Zijl (2007), the ultimate tensile strength of ECC was not significantly impacted by loading rate, although the first breaking strength was. The PVA fiber on the strain-hardening cementitious composites fracture surface was examined by Mechtcherine et al. (2011b). They discovered that under dynamic load, the PVA fiber's surface displayed wavy plastic deformation, but at the fracture point, the PVA fiber's surface resembled the original surface of fiber when pulled out during the test. Tensile strain capacity would decrease with changes in fiber strength, fiber stiffness, and fiber–matrix interface bond strength when the strain rate is increased in the range of 10^{-5} /s–10^{-1} /s (Khan et al., Jul. 2023). Gao et al. (2023) extensively studied the loading rate effect on the G_f of ECC. They found that the $CMOD_c$ value falls and the hardened portion of the load–CMOD curve shortens with increasing loading rate, suggesting a weakening of the strain hardening of ECC and a reduction in ductility. The G_f of a beam made of ECC increased by 6.5% 16.5%, and 20.8%, respectively, at loading rates of 0.01 mm.s^{-1}, 0.1 mm.s^{-1}, and 0.1 mm.s^{-1}, as compared to 0.0004 mm.s^{-1}. This suggests that less energy is used for crack propagation in ECC, which weakens ductility and the strain capacity. Conversely, the energy needed for the expansion and cracking of high-strength concrete and ultra-high-performance fiber-reinforced all vary in a specific range of loading rates (Abid et al., 2018).

5.7 Effect of Notch Depth

The depth notch ratio is the ratio the of depth of the notch to the height of the sample. The fracture energy exhibits a decreasing trend as the notch depth ratio rises from 0.3 to 0.8 while maintaining a constant sample height of 100 mm (Abd Elmoaty et al., 2108). Similar trend has also been noticed in normal concrete (Maalej et al., 1995). In a study it was revealed a decrease in fracture energy as the initial notch depth ratio increases from 0.1 to 0.2. During three-point bending failure, the primary crack within the ECC specimen exhibited a zigzag propagation pattern. For specimens with shallower initial notches (0.1 and 0.2), a potential for combined shear failure at the notch tip might exist due to a larger fracture zone height. This phenomenon is likely caused by the interplay between the normal stress induced by bending and the shear stress arising from interfacial slip between the fiber and the matrix (Li et al., 2011b; Mechtcherine et al., 2011a). Fig. 8 below shows the effect of notch depth on the fracture energy of ECCs. The graph illustrates the relationship between notch depth ratio (x-axis) and fracture energy (y-axis) based on data from Gao et al. 2022. It shows a non-linear trend where fracture energy initially fluctuates at lower notch depth ratios, peaks at approximately 0.3 notch depth ratio with a maximum fracture energy of around 3.8 kJ/m^2, and then steadily decreases as the notch depth ratio increases, reaching its lowest value of about 1.5 kJ/m^2 at the highest ratio. This suggests that an optimal notch depth ratio exists around 0.3, maximizing fracture energy, while both lower and higher ratios result in reduced fracture energy.

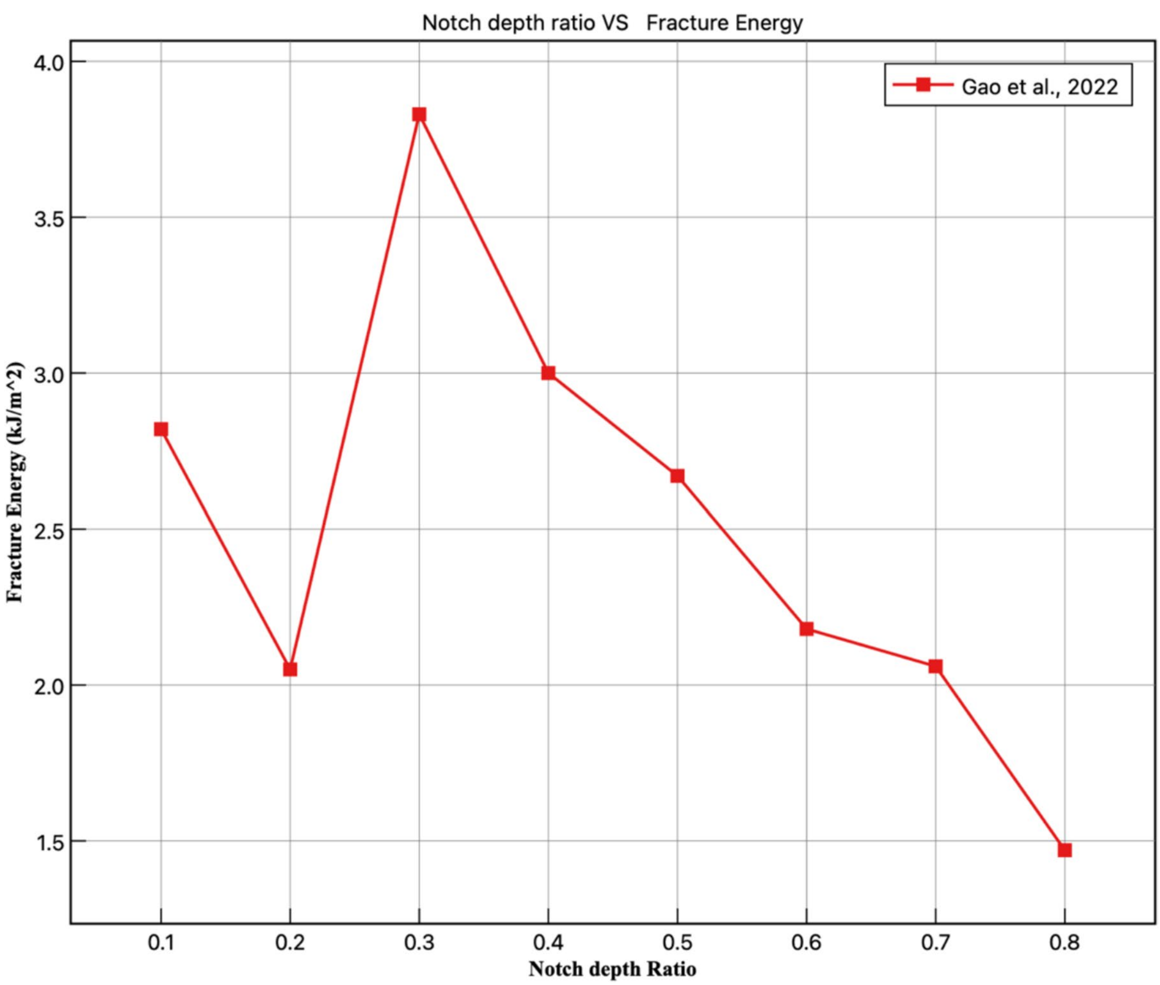

Fig. 8 G_f variations for notch depth ratio (Abd Elmoaty et al., 2108)

5.8 Effect of Temperature

An interesting trend emerged when analyzing the bi-material specimens' fracture properties at varying temperatures. Both fracture toughness and fracture energy reached their peak values at 400 °C. Below this temperature, fracture toughness steadily increased with rising temperature. However, above 400 °C, a rapid decrease was detected. This behavior can be ascribed to the dominant failure mode at different temperatures. Below 400 °C, adhesive failure between the materials was prevalent. As the temperature rose, concrete cracking increased. The ECC effectively filled these cracks near the interface, leading to enhanced interfacial fracture toughness. However, higher temperatures also weakened the concrete itself, causing its fracture toughness to decline. At 400 °C, a critical point was reached where the concrete's fracture toughness became lower than the interface's. This triggered a shift towards cohesive failure within the concrete, resulting in the observed peak in overall toughness. Further temperature increases beyond 400 °C continued to degrade the concrete's fracture toughness due to thermal damage, leading to the observed decline. The trend for fracture energy was more complex. At temperatures below 400 °C, it initially decreased before increasing. Above 400 °C, a sharp drop in fracture energy mirrored the decrease in toughness (Shang et al., 2023). Alternatively, an increasing trend has been found in the G_f of the ECC mix when the temperature drops from 20 to − 20 (Gao et al., 2023). In a further investigation, the effects of freeze and thaw in ECC were measured at − 20 and 20 degrees. After 25 freeze–thaw cycles, it has been noted that *Gf* decreases when loaded at 20 °C. This is associated with the matrix and fiber–matrix interface performance degrading as a result of the freeze–thaw cycles the specimen's quality and dynamic elastic modulus increased, however, there was some surface degradation, and a few new pores formed. According to a previous study, this is due to the micro-ice crystals in the pores acting as a cryopump (Gao & Xie, 2022a). The specimen may be supersaturated during the freezing and thawing process because water is pushed from the gel pores and micropores to the area where the micro-ice crystals are during the freeze and thawing phase. Throughout the temperature recovery process, the water migrates in the opposite direction. As a result, it seems to absorb water during the whole freeze–thaw cycle when there is water outdoors. Consequently, ECC's quality and dynamic elasticity seem to improve after 25 freeze–thaw cycles(Gao & Xie, 2022a). The effect of temperature and freeze–thaw cycles on fracture energy is shown in Fig. 9. Shang et al. (2023) shows a complex pattern where the fracture energy starts around 2.8 J/m^2 at lower temperatures, fluctuates with a notable peak reaching about 3.0 J/m^2 at around 400 °C, and then steadily decreases to about 1.2 J/m^2 as temperature increases to 700 °C. Gao and Xie (2022a) only cover a shorter temperature range from about −100 °C to 0 °C, showing some variation in fracture energy between approximately 1.7 and 2.5 J/m^2.

6 Conclusion

For engineered cementitious composites (ECC), fracture energy is important because it indicates how resistant the material is to crack propagation. In ECC, higher fracture energy corresponds to improved toughness and the capacity to absorb energy before failure. This enhanced resistance to cracks reduces spalling and increases the

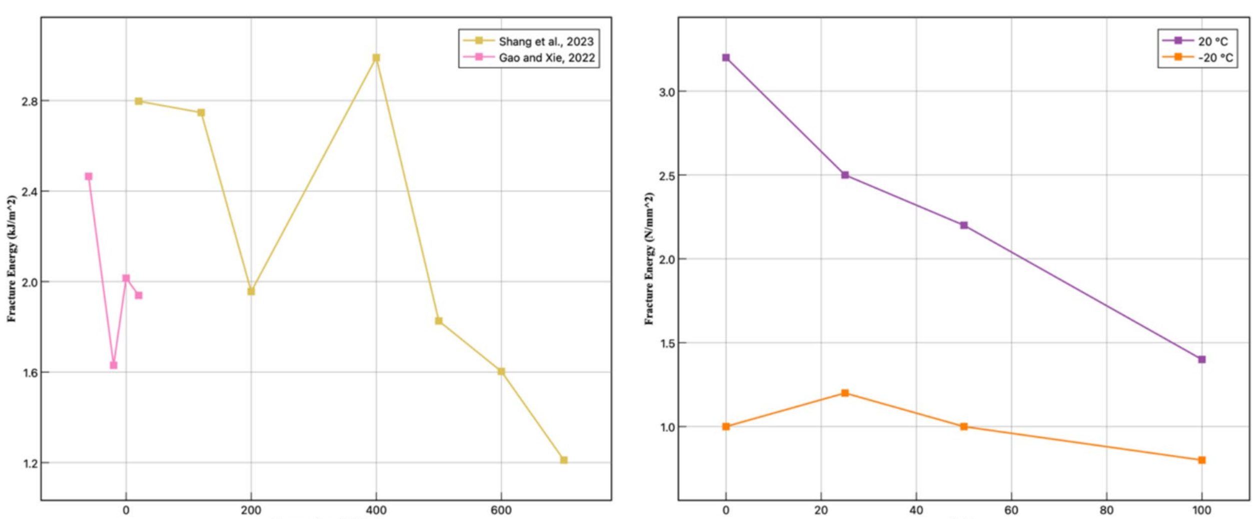

Fig. 9 Effect of temperature and freeze–thaw cycles on fracture energy (Gao et al., 2023) (Al Moman et al., 2023) (Shiping et al., 2022)

overall longevity of structures, particularly in adverse environments or during seismic activity. The characteristics of the binding matrix, the type, volume, and aspect ratio of the fiber, as well as the strength of the link between the fiber and matrix, all affect fracture energy in ECC. ECCs with tailored fracture behavior for a variety of engineering applications can be created by optimizing these factors. Because of its remarkable ductility, tensile strength, and crack control, engineered cementitious composites (ECC) with high fractured energy are appropriate for a range of civil engineering applications. ECC's strain-hardening behavior lowers material consumption and improves sustainability in bridge building, while its impact resistance and energy absorption capacity increase the longevity of girders and piers (Baral et al., 2019; Krouma & Syed, 2016). ECC's high ductility improves beam–column joint performance for earthquake-resistant structures, lowering the demand for shear reinforcement and boosting resilience in seismic events (Yuan et al., 2017; Zhang et al., 2015).

In repair and retrofitting, ECC is also effective as its bonding with the traditional concrete is very well in the repair of deep beams in aging structures (Liew et al., 2020; Şahmaran et al., 2013). The self-healing properties further reduced the maintenance needs (Khitab et al., 2012). The freeze and thaw resistance of ECC improves its durability and ensures long-lasting performance in tunnels and dams (Gao & Xie, 2022b).

- **Fiber type**: Fiber types play an important role in the mechanical characterization of ECC. Among the different types of fibers studied for fracture energy of ECC, PVP fibers are the best-performing synthetic type of fiber. The G_f of the combined PVA and glass fibers was lower than the fracture energy of the sample containing only 1% of PVA fibers.
- **Fiber vol. and aspect ratio**: Similar to the fiber volume, the aspect ratio of fiber also plays a significant role in the fracture energy of ECC. As the volume content of PVA fiber rose from 1.0% to 2%, correspondingly, the fracture energy increased by 47.9% and 112.8%. This suggests that the addition of PVA fiber to an ECC within the range of 1.0–1.5% is beneficial in getting the desired fracture energy. The G_f of PE-ECC improved gradually from 10.08 kJ/m^2 to 16.04 kJ/m^2 as the aspect ratio of fiber value increased from 5 to 18.
- **Effect of w/c ratio**: When the w/b ratio increased from 0.24 to 0.28, respectively, the G_f increased by 26.9% and 18.4%. This suggests that in contrast to ECC with PVA fibers, whose energy dissipation capacity increased with an increasing w/b ratio, PVA-ECC's energy dissipation capacity can be strengthened with an increase in the w/b ratio. This is mostly because a lower water-to-binder ratio corresponds to a higher interfacial friction force between the matrix and the fiber as well as a more energy consumption during the pulling out of the fiber, which raises the G_f.
- Depending on the type of specimen used for fracture energy calculation also affects the fracture behavior of ECCs. With the notch sample, the depth of the notch ratio controls the fracture energy of the ECCs. The specimen's fracture energy has been recorded low with the initial notch depth ratio. The primary crack in the ECC developed in the form of a zigzag when the three-point bending beam failed. This is due to the combination of normal and shear stress from bending test between the fiber and matrix of cementitious composites. The depth and geometry of the notch are measured using digital calipers or other precise measurement tools, and the dimensions are verified against design specifications. Any deviation is recorded and reported to account for its influence on fracture energy results.
- Similarly, for the dynamic behavior of ECC, the loading rate also affects the G_f of ECC. The dynamic peak load and the G_f increase with factors around 2.5 and 3.5, correspondingly, at the fastest loading rate of 10^3 mm/s compared to 10^{-3} mm/s. To ensure accuracy, the loading rate must be calibrated before the test, and any variations are logged through the machine's integrated data acquisition system. Standard rates recommended by ASTM or ISO guidelines should be typically followed unless deviations are explicitly justified.

7 Future Recommendations

- **Multi-scale model development and simulation:** There is still a need to investigate the creation of multi-scale models that integrate microstructure, fiber–matrix interactions, and the general fracture behavior of ECC. This can help to optimize the distribution and characteristics of the fiber for the desired fracture energy.
- **Advanced fiber engineering:** Recent innovations in new fiber types, such as hybrid and nanofibers, and surface modifications can increase stress transfer and the fiber–matrix interface, which could result in higher fracture energy. There is a lack of studies on the fracture energy and fracture behavior of ECCs.
- **Sustainable ECC development**: There is a lack of research being done on the fracture behavior of sustainable materials like the use of recycled aggregates,

and other waste materials to make more sustainable ECCs for a green environment. Achieving sustainable engineered cementitious composites (ECC) involves integrating alternative materials, optimizing design, and employing innovative production techniques. Utilizing waste materials like fly ash and silica fume, as well as natural fibers, reduces environmental impact while enhancing mechanical and thermal properties. Design improvements, such as using PVA fibers for ductility and strain-hardening, allow for lighter structures with extended lifespans, minimizing material usage and repairs. Sustainable production methods, including alkali-activated cements, nano-engineering, and recycled aggregates, further reduce carbon emissions. ECC's durability and self-healing capabilities make it ideal for critical infrastructure, promoting long-lasting and eco-friendly construction.

- **Breakage toughness under various loading situations:** The current knowledge of ECC fracture energy includes loading that is not monotonic in the real world like fatigue, impact, and combination loading scenarios.
- **Experimental limitations:** Non-standardized methods for evaluating ECC fracture energy hinder result comparability. The three-point bending test offers simplicity and direct measurements, but underestimates fracture energy by missing complex crack interactions. Uniaxial tensile tests provide tensile strain data, but fail to reflect multi-axial stress states. However, Wang et al. reported that acoustic emission (AE) monitoring enhances understanding of crack behavior with real-time data but requires sophisticated equipment, limiting accessibility and standardization (Wang et al., 2023). They also reported that further investigation is needed on the experimental procedure of the AE monitoring method for the fracture analysis of ECC.

Abbreviations

G_f	Fracture energy
$G_{f,S}$	Fracture energy due to strain softening
$G_{f,H}$	Fracture energy due to strain hardening
P-CMOD	Load crack mouth opening displacement
PVA	Polyvinyl alcohol
PE	Polyethylene
POFA	Petroleum oil fly ash
PP	Polypropylene
FRC	Fiber-reinforced concrete

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Author contributions
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References

Abd Elmoaty, A. E. M., Morsy, A. M., & Harraz, A. B. (2022). Effect of fiber type and volume fraction on fiber reinforced concrete and engineered cementitious composite mechanical properties. *Buildings, 12*(12), 2108. https://doi.org/10.3390/buildings12122108

S. R. Abid, M. S. Shamkhi, N. S. Mahdi, and Y. H. Daek, "Mechanical properties of PP-based engineered cementitious composites," *International Conference on Advances in Sustainable Engineering and Applications, ICASEA 2018 - Proceedings*, pp. 142–146, 2018, https://doi.org/10.1109/ICASEA.2018.8370972.

B. Akcay, M. T.-C. and B. Materials, and undefined 2012, "Mechanical behaviour and fibre dispersion of hybrid steel fibre reinforced self-compacting concrete," *ElsevierB Akcay, MA TasdemirConstruction and Building Materials, 2012•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0950061811004776

Al Moman, A., Butt, A. A., & Nassiri, S. (2023). Feasibility assessment of self-deicing concrete pavements with recycled CFRP reinforcement: Environmental and mechanical performance. *Resources, Conservation and Recycling, 198*, 107213. https://doi.org/10.1016/J.RESCONREC.2023.107213

Arslan, A. (1995). Mixed-mode fracture performance of fibre reinforced concrete under impact loading. *Materials and Structures, 28*(8), 473–478. https://doi.org/10.1007/BF02473167

Baloch, H., Grünewald, S., & Matthys, S. (2022). Different approaches for FEM modelling of strain-hardening cementitious composites. *RILEM Bookseries, 36*, 389–399. https://doi.org/10.1007/978-3-030-83719-8_34

N. Banthia, N. N.-C. and C. Composites, and undefined 2003, Crack growth resistance of hybrid fiber reinforced cement composites, *ElsevierN Banthia, N NandakumarCement and Concrete Composites, 2003•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0958946501000439

N. Banthia, N. N.-C. and C. Composites, and undefined 2003, "Crack growth resistance of hybrid fiber reinforced cement composites," *ElsevierN Banthia, N NandakumarCement and Concrete Composites, 2003•Elsevier*, [Online]. Retrieved May 01, 2024 from https://www.sciencedirect.com/science/article/pii/S0958946501000439

Baral, K., Tatar, J., & Zhang, Q. (2019). High-performance impact-resistant concrete mixture for transportation infrastructure applications. *Transportation Research Record: Journal of the Transportation Research Board, 2673*(12), 628–635. https://doi.org/10.1177/0361198119873326

Barros, J. A. O., & Cruz, J. S. (2001). Fracture energy of steel fiber-reinforced concrete. *Mechanics of Advanced Materials and Structures, 8*(1), 29–45. https://doi.org/10.1080/10759410119428

S. H. Basha, X. Lian, W. Hou, P. Zheng, and Z. Guo, Behavior of Short Columns Constructed using Engineered Cementitious Composites under Seismic Loads. 2021, https://doi.org/10.21203/RS.3.RS-1095304/V1.

W. Boshoff, G. V. Z.-C. and concrete research, and undefined 2007, Time-dependent response of ECC: Characterisation of creep and rate dependence, *ElsevierWP Boshoff, GPAG Van ZijlCement and concrete research, 2007•Elsevier*, [Online]. Retrieved April 27, 2024 from https://www.sciencedirect.com/science/article/pii/S0008884607000361

Boshoff, W. P., & van Zijl, G. P. A. G. (2007). Time-dependent response of ECC: Characterisation of creep and rate dependence. Cement and concrete research, 37(5), 725–734. https://doi.org/10.1016/j.cemconres.2007.02.001

I. Del Bosque, W. Zhu, T. Howind, … A. M.-C. and C., and undefined 2017, "Properties of interfacial transition zones (ITZs) in concrete containing recycled mixed aggregate," *ElsevierIFS Del Bosque, W Zhu, T Howind, A Matías, MIS De Rojas, C MedinaCement and Concrete Composites, 2017•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0958946517304006

Cao, M., Xu, L., & Zhang, C. (2015). Review on micromechanical design, performance and development tendency of engineered cementitious composite. *Kuei Suan Jen Hsueh Pao/journal of the Chinese Ceramic Society, 43*(5), 632–642. https://doi.org/10.14062/j.issn.0454-5648.2015.05.12

Y. Ding, C. Shi, N. L.-C. and B. Materials, and undefined 2018, "Fracture properties of slag/fly ash-based geopolymer concrete cured in ambient temperature," *ElsevierY Ding, CJ Shi, N LiConstruction and Building Materials, 2018•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0950061818323201

Ding, Y., Tao Yu, J., Yu, K. Q., & Lang Xu, S. (2018). Basic mechanical properties of ultra-high ductility cementitious composites: From 40 MPa to 120 MPa. *Composite Structures, 185*, 634–645. https://doi.org/10.1016/J.COMPSTRUCT.2017.11.034

"Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC)," *Durability of Strain-Hardening Fibre-Reinforced Cement-Based Composites (SHCC)*, 2011, https://doi.org/10.1007/978-94-007-0338-4.

Etminani, M. A., & Sharif, F. (2018). Debonding mechanism of polymeric fibers in reinforced cementitious composites as a function of crystallinity degree of fibers. *Journal of Composite Materials, 52*(3), 383–394. https://doi.org/10.1177/0021998317707567

S. Gao and P. Xie, Effect of temperatures and moisture content on the fracture properties of engineered cementitious composites (ECC), *Materials*. https://doi.org/10.3390/MA15072604.

Gao, S., Gao, R., Mu, R., Zhu, Y., & Qi, L. (2023). Effect of loading rate on mode I/mode II/mixed mode I-II fracture performance of engineered cementitious composites. *International Journal of Solids and Structures, 262–263*, 112052. https://doi.org/10.1016/J.IJSOLSTR.2022.112052

Gao, S., Gao, R., & Zhu, Y. (2023). Effect of notch depth ratio and specimen width on mode II fracture properties of ECC. *Journal of Building Engineering, 74*, 106980. https://doi.org/10.1016/J.JOBE.2023.106980

Gao, S., Meng, H., Zhu, Y., & Xie, P. (2023). Impact of low temperature and NaCl attack on the fracture properties of engineered cementitious composites (ECC). *Journal of Building Engineering, 76*, 107114. https://doi.org/10.1016/J.JOBE.2023.107114

Gao, S., Qi, L., Zhu, Y., & Wang, W. (2022). Effect of notch depth ratio on mode I and mixed mode I-II fracture properties of engineered cementitious composites (ECC). *International Journal of Solids and Structures, 236–237*, 111363. https://doi.org/10.1016/J.IJSOLSTR.2021.111363

Gao, S., Shao, W., Qiao, J., et al. (2012). Toughness of ECC evaluated by nominal fracture energy. *Applied Mechanics and Materials*. https://doi.org/10.4028/www.scientific.net/AMM.238.57

Gao, S., & Xie, P. (2022b). Effect of temperatures and moisture content on the fracture properties of engineered cementitious composites (ECC). *Materials*. https://doi.org/10.3390/MA15072604

Guan, Y., Li, Y., Zhang, H., Sun, R., Tian, J., & Yang, Y. (2023). Preparation of low-cost green engineered cementitious composites (ECC) using gold tailings and unoiled PVA fiber. *Journal of Building Engineering, 78*, 107455. https://doi.org/10.1016/J.JOBE.2023.107455

Gupta, S., Esmaeeli, H. S., & Moini, R. (2024). Tough and ductile architected nacre-like cementitious composites. *Advanced Functional Materials*. https://doi.org/10.1002/ADFM.202313516

T. Huang, Y. Z.-C. & Structures, and undefined 2016, Numerical modelling of mechanical behaviour of engineered cementitious composites under axial tension, *ElsevierT Huang, YX ZhangComputers & Structures, 2016•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0045794916303844

T. Huang, Y. Zhang, C. Y.-E. F. Mechanics, and undefined 2016, Multiscale modelling of multiple-cracking tensile fracture behaviour of engineered cementitious composites, *ElsevierT Huang, YX Zhang, C YangEngineering Fracture Mechanics, 2016•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0013794416301588

Johari, M. A. M., Altwair, N. M., & Hashim, S. F. S. (2015). Fracture and tensile characteristics of engineered cementitious composites containing POFA. *Advances in Cement Research, 25*(4), 189–199. https://doi.org/10.1680/ADCR.11.00056

L. Kan, H. Shi, A. S.-A. M. Journal, and undefined 2010, Self-Healing Characterization of Engineered Cementitious Composite Materials., *acemrl.engin.umich.eduLL Kan, HS Shi, AR Sakulich, VC LiACI Materials Journal, 2010•acemrl.engin.umich.edu*, 2010, [Online]. Retrieved May 02, 2024 from http://acemrl.engin.umich.edu/wp-content/uploads/sites/412/2018/10/Self-Healing-Characterization-of-Engineered-Cementitious-Composites-ECC.pdf

T. Kanda, V. L.-J. of advanced concrete technology, and undefined 2006, "Practical design criteria for saturated pseudo strain hardening behavior in ECC," *jstage.jst.go.jpT Kanda, VC LiJournal of advanced concrete technology, 2006•jstage.jst.go.jp*, [Online]. Retrieved May 01, 2024 from https://www.jstage.jst.go.jp/article/jact/4/1/4_1_59/_article/-char/ja/

Kanda, T., Lin, Z., & Li, V. C. (2000). Tensile stress-strain modeling of pseudostrain hardening cementitious composites. *Journal of Materials in Civil Engineering, 12*(2), 147–156. https://doi.org/10.1061/(ASCE)0899-1561(2000)12:2(147)

Khan, S. W., et al. (2023). Performance evaluation of the fresh and hardened properties of different PVA-ECC mixes: An experimental approach. *Case Studies in Construction Materials, 18*, e01764. https://doi.org/10.1016/j.cscm.2022.e01764

Khitab, A., Nadeem, M., & Hussain, S. (2012). Use of flexible engineered cementitious composite in buildings. *Key Engineering Materials, 510–511*(1), 591–596. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/KEM.510-511.591

Kim, S., Park, C., & Kim, Y. (2020). Effect of SIFRCCs with varying steel fiber volume fractions on flexural behavior. *Applied Sciences*. https://doi.org/10.3390/APP10062072

Y. Kitsutaka, Y. Uchida, H. Mihashi, Y. Kaneko, S. Nakamura, and N. Kurihara, Draft on the JCI Standard Test Method for Determining Tension Softening Properties of Concrete, 2001.

Krouma, A., & Syed, Z. I. (2016). A review on the use of engineered cementitious composite in bridges. *Materials Science Forum, 860*, 125–134. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/MSF.860.125

Lan, M., Zhou, J., & Xu, M. (2021). Effect of fibre types on the tensile behaviour of engineered cementitious composites. *Frontiers in Materials*. https://doi.org/10.3389/fmats.2021.775188

E. Landis, L. B.-J. of engineering mechanics, and undefined 2002, Experiments to relate acoustic emission energy to fracture energy of concrete, J Eng Mech vol. 128, no. 6, pp. 698–702, 2002, https://doi.org/10.1061/(ASCE)0733-9399(2002)128:6(698).

B. Lee, J. Kim, Y. K.-C. & concrete, and undefined 2010, Prediction of ECC tensile stress–strain curves based on modified fiber bridging relations considering fiber distribution characteristics, *CiteseerBY Lee, JK Kim, YY KimComputers & concrete, 2010•Citeseer*, [Online]. Retrieved May 02, 2024 from https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=f32ea1c77959ca078fa8339093bb173ebd079975

V. Li and H. Wu, "Conditions for pseudo strain-hardening in fiber reinforced brittle matrix composites," 1992, [Online]. Retrieved May 01, 2024 from https://asmedigitalcollection.asme.org/appliedmechanicsreviews/article-abstract/45/8/390/421529

V. Li, Y. Lim, Y. C.-C. P. B. Engineering, and undefined 1998, "Feasibility study of a passive smart self-healing cementitious composite," *ElsevierVC Li, YM Lim, YW ChanComposites Part B: Engineering, 1998•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S1359836898000341

H. Li, S. X.-E. F. Mechanics, and undefined 2011, "Determination of energy consumption in the fracture plane of ultra high toughness cementitious composite with direct tension test," *ElsevierH Li, S XuEngineering Fracture Mechanics, 2011•Elsevier*, [Online]. Retrieved May 01, 2024 from https://www.sciencedirect.com/science/article/pii/S0013794411001202

H. Li, S. X.-E. F. Mechanics, and undefined 2011, "Determination of energy consumption in the fracture plane of ultra high toughness cementitious composite with direct tension test," *ElsevierH Li, S XuEngineering Fracture Mechanics, 2011•Elsevier*, Accessed: May 02, 2024. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0013794411001202

Li, H., & Xu, S. (2011). Determination of energy consumption in the fracture plane of Ultra High Toughness Cementitious Composite with direct tension test. *Engineering Fracture Mechanics, 78*(9), 1895–1905. https://doi.org/10.1016/J.ENGFRACMECH.2011.03.012

Li, V. C., & Leung, C. K. Y. (1992). Steady-state and multiple cracking of short random fiber composites. *Journal of Engineering Mechanics, 118*(11), 2246–2264. https://doi.org/10.1061/(ASCE)0733-9399(1992)118:11(2246)

Li, V. C., Mishra, D. K., & Wu, H. C. (1995). Matrix design for pseudo-strain-hardening fibre reinforced cementitious composites. *Materials and Structures, 28*(10), 586–595. https://doi.org/10.1007/BF02473191

Liew, M. S., Aswin, M., Danyaro, K. U., Mohammed, B. S., & Al-Yacouby, A. M. (2020). Investigation of fibers reinforced engineered cementitious composites properties using quartz powder. *Materials*. https://doi.org/10.3390/MA13112428

LIQinghua: The size effect of compressive properties of ultra hig... - Google Scholar." [Online]. Retrieved May 02, 2024 from https://scholar.google.com/scholar_lookup?title=The%20size%20effect%20of%20compressive%20properties%20of%20ultra%20high%20toughness%20cementitious%20composites%20&publication_year=2015&author=Q.%20Li&author=B.%20Zhou&author=B.%20Huang

H. Ma, S. Qian, Z. Zhang, Z. Lin, V. L.-C. and building materials, and undefined 2015, Tailoring engineered cementitious composites with local ingredients, *Elsevier*. [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0950061815305675

Maalej, M., Hashida, T., & Li, V. C. (1995). Effect of fiber volume fraction on the off-crack-plane fracture energy in strain -hardening engineered cementitious composites. *Journal of the American Ceramic Society, 78*(12), 3369–3375. https://doi.org/10.1111/J.1151-2916.1995.TB07979.X

Marushchak, U., Sydor, N., & Margal, I. (2023). Impact of polypropylene fibers on the properties of engineered cementitious composites. *Lecture Notes in Civil Engineering, 290*, 262–269. https://doi.org/10.1007/978-3-031-14141-6_26

V. Mechtcherine, J. Schulze, and T. Wittek, Strain hardening cementitious composites - Material design and testing, in *Keep Concrete Attractive - Proceedings of the fib Symposium 2005*, 2005, pp. 257–262. [Online]. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85009062951&partnerID=40&md5=8cd36888c76e2e7a5b1ac02c6c20495a

V. Mechtcherine and J. Schulze, "EFFECT OF THE TEST SET-UP AND CURING CONDITIONS ON FRACTURE BEHAVIOR OF STRAIN HARDENING CEMENT-BASED COMPOSITES (SHCC)," *Measuring, Monitoring and Modeling Concrete Properties*, pp. 33–39, Sep. 2007, https://doi.org/10.1007/978-1-4020-5104-3_4.

V. Mechtcherine, O. Millon, M. Butler, K. T.-C. and Concrete, and undefined 2011a, "Mechanical behaviour of strain hardening cement-based composites under impact loading," *Elsevier*, [Online]. Retrieved May 01, 2024 from https://www.sciencedirect.com/science/article/pii/S0958946510001575

V. Mechtcherine, O. Millon, M. Butler, K. T.-C. and Concrete, and undefined 2011b, Mechanical behaviour of strain hardening cement-based composites under impact loading, *Elsevier*, [Online]. Retrieved April 27, 2024 from https://www.sciencedirect.com/science/article/pii/S0958946510001575

Niu, H. M., Xing, Y. M., & Zhao, Y. (2013). Effects of processing on fiber distribution and mechanical performance of engineered cementitious composites (ECC). *Advanced Materials Research, 709*, 122–126. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMR.709.122

H. Noorvand, G. Arce, M. M. Hassan, and T. Rupnow, "Performance of engineered cementitious composites utilizing locally available materials in the state of Louisiana," in *Proceedings, Annual Conference - Canadian Society for Civil Engineering*, 2019. [Online]. https://www.scopus.com/inward/record.uri?eid=2-s2.0-85080945925&partnerID=40&md5=5e375663eb10c1012ed9cefac217aee7

P. P.-C. and C. research and undefined 1980, "Fracture energy of concrete: Practical performance and experimental results," *ElsevierPE PeterssonCement and Concrete research, 1980•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/0008884680900551

Pakravan, H. R., Latifi, M., & Jamshidi, M. (2016). Ductility improvement of cementitious composites reinforced with polyvinyl alcohol–polypropylene hybrid fibers. *Journal of Industrial Textiles, 45*(5), 637–651. https://doi.org/10.1177/1528083714534712

Z. Pan, C. Wu, J. Liu, W. Wang, J. L.-C. and B. Materials, and undefined 2015, Study on mechanical properties of cost-effective polyvinyl alcohol engineered cementitious composites (PVA-ECC), *ElsevierZ Pan, C Wu, J Liu, W Wang, J LiuConstruction and Building Materials, 2015•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0950061814013737

Uday, N. P. (2017). Experimental determination of fracture energy by RILEM method. Int. J. Eng. Sci, *6*(03), 106–115. https://doi.org/10.9790/1813-060301106115.

S. Qian, J. Zhou, M. De Rooij, … E. S.-C. and C., and undefined 2009, Self-healing behavior of strain hardening cementitious composites incorporating local waste materials," *ElsevierS Qian, J Zhou, MR De Rooij, E Schlangen, G Ye, K Van BreugelCement and Concrete Composites, 2009•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0958946509000468

K. Rokugo, T. Kanda, T. Kanakubo, and H. Fukuyama, *Strain Hardening Cement Composites: Structural Design and Performance: State-of-the-Art Report of the RILEM Technical Committee 208-HFC, SC3*. 2013. [Online]. Retrieved May 02, 2024 from https://library.wur.nl/WebQuery/titel/2139451

Ruiz, G., Zhang, X. X., Yu, R. C., Porras, R., Poveda, E., & Del Viso, J. R. (2011). Effect of loading rate on fracture energy of high-strength concrete. *Strain, 47*(6), 518–524. https://doi.org/10.1111/J.1475-1305.2010.00719.X

M. Şahmaran, V. L.-C. and C. Research, and undefined 2007, De-icing salt scaling resistance of mechanically loaded engineered cementitious composites, *ElsevierM Şahmaran, VC LiCement and Concrete Research, 2007•Elsevier*, [Online]. Retrieved May 01, 2024 from https://www.sciencedirect.com/science/article/pii/S0008884607000920?casa_token=Fyfz9GxclEgAAAAA:1lwZhgcDbmYXuNGgHm65BWg36XsHi7oXP9dOt5mQTGT5RHFT34H_UXwt4uddMoKE_xsTjwj--vA0

Şahmaran, M., Bilici, Z., Ozbay, E., Erdem, T. K., Yucel, H. E., & Lachemi, M. (2013). Improving the workability and rheological properties of Engineered Cementitious Composites using factorial experimental design. *Composites Part B Engineering, 45*(1), 356–368. https://doi.org/10.1016/J.COMPOSITESB.2012.08.015

A. Sakulich, V. L.-C. and C. research, and undefined 2011, Nanoscale characterization of engineered cementitious composites (ECC), *ElsevierAR Sakulich, VC LiCement and Concrete research, 2011•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0008884610002334

Shang, X. Y., Zhou, Z. G., Yan, K., Wu, J. H., Li, L. Z., & Yu, J. T. (2023). Interfacial fracture performance of engineered cementitious composites and fire-damaged concrete. *Case Studies in Construction Materials, 19*, e02167. https://doi.org/10.1016/J.CSCM.2023.E02167

Shiping, Y., Boxue, W., Chenxue, Z., & Shuang, L. (2022). Bond performance between textile reinforced concrete (TRC) and brick masonry under conventional environment. *Structures, 36*, 392–403. https://doi.org/10.1016/J.ISTRUC.2021.12.029

Su, A., & Cai, Y. (2013). Influence of aspect ratio of macro synthetic fiber on mechanical properties of shotcrete. *Advanced Materials Research, 652–654*, 1226–1232. https://doi.org/10.4028/WWW.SCIENTIFIC.NET/AMR.652-654.1226

Sun, M., et al. (2018). Effect of modified polyvinyl alcohol fibers on the mechanical behavior of engineered cementitious composites. *Materials*. https://doi.org/10.3390/MA12010037

Tan, G., Zhu, Z., Wang, W., & He, X. (2022). A fractal-based approach for cracking characterization and whole process prediction exploration of PP fiber reinforced ECC containing sustainable ingredients. *Construction and Building Materials, 318*, 126015. https://doi.org/10.1016/J.CONBUILDMAT.2021.126015

X. Wang, S. Jacobsen, J. He, Z. Zhang, … S. L.-C. and C., and undefined 2009, "Application of nanoindentation testing to study of the interfacial transition zone in steel fiber reinforced mortar," *ElsevierXH Wang, S Jacobsen, JY He, ZL Zhang, SF Lee, HL LeinCement and Concrete Research, 2009•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0008884609001057

Wang, W., Xu, M., & Bao, Y. (2023). Assessment of fracture process of engineered cementitious composite (ECC) by time-frequency analysis of acoustic emission signals. *Smart Materials and Structures*. https://doi.org/10.1088/1361-665X/ACC1BA

K. Wille, A. N.-F.-7 international conference, and undefined 2010, "Fracture energy of UHP-FRC under direct tensile loading," *framcos.orgK Wille, AE NaamanFraMCoS-7 international conference, 2010•framcos.org*, [Online]. Retrieved May 02, 2024 from http://framcos.org/FraMCoS-7/01-10.pdf

K. Wille, A. N.-F.-7 international conference, and undefined 2010, "Fracture energy of UHP-FRC under direct tensile loading," *framcos.orgK Wille, AE NaamanFraMCoS-7 international conference, 2010•framcos.org*, [Online]. Retrieved May 01, 2024 from http://framcos.org/FraMCoS-7/01-10.pdf

Wittmann, F. H., Zurich, E., Mihashi, H., Wiltmann, F. H., Mihashi, H., & Nomura, N. (1990). Size effect on fracture energy of concrete. *Engineering Fracture Mechanics, 35*(3), 107. https://doi.org/10.1016/0013-7944(90)90188-M

M. Wu, B. Johannesson, M. G.-C. and B. Materials, and undefined 2012, A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material, *ElsevierM Wu, B Johannesson, M GeikerConstruction and Building Materials, 2012•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0950061811005198

Wu, H. C., & Li, V. C. (1992). Snubbing and bundling effects on multiple crack spacing of discontinuous random fiber-reinforced brittle matrix composites. *Journal of the American Ceramic Society, 75*(12), 3487–3489. https://doi.org/10.1111/J.1151-2916.1992.TB04457.X

Xu, B. W., Ju, J. W., & Shi, H. S. (2011). Progressive micromechanical modeling for pullout energy of hooked-end steel fiber in cement-based composites. *International Journal of Damage Mechanics, 20*(6), 922–938. https://doi.org/10.1177/1056789510385260

Xu, L., Pan, J., Leung, C. K. Y., & Yin, W. (2018). Shaking table tests on precast reinforced concrete and engineered cementitious composite/reinforced concrete composite frames. *Advances in Structural Engineering, 21*(6), 824–837. https://doi.org/10.1177/1369433217733759

Y. Yang, M. Lepech, E. Yang, V. L.-C. and C. Research, and undefined 2009, "Autogenous healing of engineered cementitious composites under wet–dry cycles," *ElsevierY Yang, MD Lepech, EH Yang, VC LiCement and Concrete Research, 2009•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0008884609000222

G. B. Yang and Z. Li, Experimental Study on Ultra-lightweight Fire-resistive Engineered Cementitious Composite, *Proceedings of the 2nd Annual International Conference on Advanced Material Engineering (AME 2016)*, 2016, https://doi.org/10.2991/AME-16.2016.25.

K. Yu, J. Yu, Z. Lu, Q. C.-E. F. Mechanics, and undefined 2015, "Determination of the softening curve and fracture toughness of high-strength concrete exposed to high temperature," *ElsevierK Yu, J Yu, Z Lu, Q ChenEngineering Fracture Mechanics, 2015•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0013794415006025

Yu, J., Yu, K., & Lu, Z. (2012). Residual fracture properties of concrete subjected to elevated temperatures. *Materials and Structures/materiaux Et Constructions, 45*(8), 1155–1165. https://doi.org/10.1617/S11527-012-9823-4

Yu, K., Ding, Y., Liu, J., & Bai, Y. (2020). Energy dissipation characteristics of all-grade polyethylene fiber-reinforced engineered cementitious composites (PE-ECC). *Cement and Concrete Composites, 106*, 103459. https://doi.org/10.1016/J.CEMCONCOMP.2019.103459

Yu, K., Li, L., Yu, J., Wang, Y., Ye, J., & Xu, Q. F. (2018). Direct tensile properties of engineered cementitious composites: A review. *Construction and Building Materials, 165*, 346–362. https://doi.org/10.1016/J.CONBUILDMAT.2017.12.124

Yu, K., & Lu, Z. (2014). Determining residual double-K fracture toughness of post-fire concrete using analytical and weight function method. *Materials and Structures/materiaux Et Constructions, 47*(5), 839–852. https://doi.org/10.1617/S11527-013-0097-2

Yu, K., Yu, J., Lu, Z., & Chen, Q. (2016). Fracture properties of high-strength/high-performance concrete (HSC/HPC) exposed to high temperature. *Materials and Structures/materiaux Et Constructions, 49*(11), 4517–4532. https://doi.org/10.1617/S11527-016-0804-X

Yuan, F., Pan, J., & Leung, C. K. Y. (2017). Elastoplastic time history analysis of reinforced engineered cementitious composite or engineered cementitious composite–concrete composite frame under earthquake action. *Advances in Structural Engineering, 20*(4), 491–503. https://doi.org/10.1177/1369433216655809

B. Zegardło, M. Szeląg, P. O.-C. and B. Materials, and undefined 2016, "Ultra-high strength concrete made with recycled aggregate from sanitary ceramic wastes–The method of production and the interfacial transition zone," *ElsevierB Zegardło, M Szeląg, P OgrodnikConstruction and Building Materials, 2016•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S0950061816310406

X. Zhang, C. Rena, G. Ruiz, … M. T.-I. J. of, and undefined 2010, Effect of loading rate on crack velocities in HSC, *ElsevierXX Zhang, CY Rena, G Ruiz, M Tarifa, MA CamaraInternational Journal of Impact Engineering, 2010•Elsevier*, [Online]. Retrieved April 27, 2024 from https://www.sciencedirect.com/science/article/pii/S0734743X09001833

J. Zhang, Z. Wang, X. J.-C. P. B. Engineering, and undefined 2013, "Application of ductile fiber reinforced cementitious composite in jointless concrete pavements," *ElsevierJ Zhang, Z Wang, X JuComposites Part B: Engineering, 2013•Elsevier*, [Online]. Retrieved May 02, 2024 from https://www.sciencedirect.com/science/article/pii/S135983681300053X

X. Zhang, A. A. Elazim, G. Ruiz, R. Y.-I. J. of Impact, and undefined 2014, Fracture behaviour of steel fibre-reinforced concrete at a wide range of loading rates, *ElsevierXX Zhang, AM Abd Elazim, G Ruiz, RC YuInternational Journal of Impact Engineering, 2014•Elsevier*, [Online]. Retrieved April 27, 2024 from https://www.sciencedirect.com/science/article/pii/S0734743X14001067

Zhang, J., Wang, Z., Wang, Q., & Gao, Y. (2016). Simulation and test of flexural performance of polyvinyl alcohol–steel hybrid fiber reinforced cementitious composite. *Journal of Composite Materials, 50*(30), 4291–4305. https://doi.org/10.1177/0021998316636206

Zhang, R., Matsumoto, K., Hirata, T., Ishizeki, Y., & Niwa, J. (2015). Application of PP-ECC in beam–column joint connections of rigid-framed railway bridges to reduce transverse reinforcements. *Engineering Structures, 86*, 146–156. https://doi.org/10.1016/J.ENGSTRUCT.2015.01.005

Zhang, W., Yin, C., Ma, F., & Huang, Z. (2018). Mechanical properties and carbonation durability of engineered cementitious composites reinforced by polypropylene and hydrophilic polyvinyl alcohol fibers. *Materials*. https://doi.org/10.3390/MA11071147

Zhao, D., Wang, C., Li, K., Zhang, P., Cong, L., & Chen, D. (2022). An experimental and analytical study on a damage constitutive model of engineered cementitious composites under uniaxial tension. *Materials*. https://doi.org/10.3390/MA15176063

Zhou, Y., Xi, B., Yu, K., Sui, L., & Xing, F. (2018). Mechanical properties of hybrid ultra-high performance engineered cementitious composites incorporating steel and polyethylene fibers. *Materials*. https://doi.org/10.3390/MA11081448

Zhu, M., Chen, B., Wu, M., & Han, J. (2023). Energy evolution characteristics of engineered cementitious composites (ECC) under tensile and compressive loading. *Journal of Building Engineering, 78*, 107711. https://doi.org/10.1016/J.JOBE.2023.107711

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