Advancements and Perspectives in Engineered Cementitious Composites (ECC): A Comprehensive Review

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Abstract:

Engineered Cementitious Composites (ECC) have garnered significant attention within the construction industry due to their exceptional mechanical properties and durability. This thorough review presents a meticulous analysis of the progress and prospects in ECC research. It commences by introducing the background and rationale for investigating ECC, while outlining the objectives of the review. The review provides an encompassing overview of ECC, encompassing its definition, characteristics, historical development, composition, and constituent materials. Emphasis is placed on the examination of ECC's mechanical properties, specifically its flexural behaviour, tensile behaviour, compressive strength, and resistance to environmental factors. Furthermore, the rheological properties of ECC, including workability, flowability, self-healing, crack mitigation, viscosity, and thixotropy, are discussed in detail. The review delves into the influence of fibre reinforcement on ECC, encompassing the types of fibres utilised, their impact on mechanical and structural properties, as well as fibre dispersion and orientation. Additionally, it explores the diverse applications of ECC across various fields, such as structural applications and sustainable building practices. The challenges and limitations associated with ECC, such as cost and availability, are addressed, alongside an exploration of future trends and research directions.

Keywords: Engineered Cementitious Composites (ECC), durability, workability, crack mitigation, fibre reinforcement

1. Introduction

Engineered Cementitious Composites (ECC) have attracted considerable research interest due to their unique mechanical properties and potential applications in the construction industry. ECC is a fibre-reinforced cementitious material that exhibits exceptional tensile strain capacity, crack control, and durability. The development of ECC can be traced back to the pioneering work of Victor C. Li and his research group in the 1990s (Li, 1998). Extensive research has been conducted to explore various aspects of ECC, aiming to enhance its mechanical performance, optimise its matrix design and expand its application scope. Studies have investigated the direct tensile properties of ECC, focusing on factors influencing its behaviour and strain-hardening response (Yu et al., 2018; Li et al., 2001). The use of discontinuous micro-fibres as intrinsic reinforcement for ductile ECC has been explored to enhance its toughness and structural performance (Zhang et al., 2020). Polyvinyl alcohol (PVA) fibres have been a popular choice for reinforcement due to their favourable dispersion characteristics and strain-hardening behaviour (Lee et al., 2009).

Researchers have also studied the matrix design of ECC, with a particular emphasis on achieving waterproofing properties and enhancing its performance in harsh environments (Yu et al., 2017; Zhang et al. 2023; Shumuye et al. 2023). Additionally, the sustainability of ECC and its applications in infrastructure have been addressed to promote environmentally friendly construction practices (Li, 2019; Zhu et al. 2021; Mishra et al. 2023). The use of novel cement-based composites for the strengthening and repair of concrete structures has also been explored, contributing to the development of ECC applications (Mechtcherine, 2013). High-performance fibre-reinforced cement composites, including ECC, have gained attention in Japan, leading to their practical applications in various structural elements (Rokugo et al., 2009). These studies collectively provide valuable insights into the mechanical properties, matrix design, sustainability, and practical applications of ECC. The knowledge gained from these investigations has contributed to advancing the understanding and utilisation of ECC in the construction industry. Li et al. (2023) provided a critical review and novel insights into the micromechanics of ECC. They synthesize existing research findings, addressing key aspects such as fibre-matrix interactions, crack propagation mechanisms, and strain-hardening behaviour. Additionally, the paper offers new perspectives on ECC behaviour, highlighting the importance of interface modification, fibre dispersion, and matrix design. The comprehensive review enhances understanding of ECC's unique properties and performance, paving the way for future advancements in material design and structural applications.

This review on Engineered Cementitious Composites (ECC) is driven by the increasing interest in its potential within the construction industry. ECC has gained prominence due to its impressive mechanical properties and durability, rendering it appealing for diverse construction applications. Beyond its structural benefits, ECC holds promise for sustainable construction, aligning with growing environmental concerns. To harness ECC's full advantages, a thorough examination of its advancements and perspectives is essential. This comprehensive review aims to consolidate existing knowledge, offering insights into ECC's properties, performance, and limitations. By analysing its mechanical and rheological features, investigating fibre reinforcement impacts, exploring applications, and addressing challenges, this review aspires to guide further research and development. While serving as a valuable resource for researchers and practitioners, it outlines the scope and limitations, excluding specific applications and non-English studies. Despite these constraints, this review provides essential insights into ECC, encouraging continued exploration of its potential to revolutionize the construction industry through sustainable and innovative practices.

2. Overview of Engineered Cementitious Composites (ECC)

Engineered Cementitious Composites (ECC) are distinguished by multiple cracking and fibre bridging, enhancing tensile strain capacity and crack control (Suthiwarapirak et al., 2004). Its superior adhesion to steel bridge decks makes ECC ideal for construction and repair, demonstrating resilience to dynamic loading in infrastructure applications (Ma et al. 2018). ECC's versatility includes high ductility, energy dissipation, and impact resistance for structures under severe loading (Yu et al. 2020; Chowdary & Asadi, 2021). Different fibres, like polymer fibres, enhance ECC's strength, while various aggregates influence fracture energy characteristics (Sherir et al. 2014; Said et al. 2015; Zhu et al. 2022; Shabakhty et al. 2024). ECC's low drying shrinkage minimizes cracking, improving long-term durability (Zhang et al. 2009; Zheng et al. 2022; Yang et al. 2024). It also boasts excellent rheological properties, ensuring easy placement and enhanced workability (Yücel et al. 2021), making ECC a suitable choice for applications demanding crack-free and durable concrete. The composition of Engineered Cementitious Composites (ECC) typically includes cement, fine silica sand, fly ash, polymeric fibres, water, and high-range water reducer admixtures (HRWRA). The presence of coarse aggregates can impact the ductile behaviour of cementitious composites. Li (2007) proposed a mix design proportion for ECC, which is outlined in Table 1.

Table 1. Mix design proportions of ECC Li (2007)

Mix ID	Cement	Fly ash	Sand	Water	HRWRA	Fibre (Vol %)
ECC- M45	1.0	1.2	0.8	0.56	0.012	0.02

Researchers have explored alternatives to silica sand and cement in Engineered Cementitious Composites (ECC), including different admixtures and local sand (Ajith et al. 2021; Shanmugasundaram et al. 2021; Hou et al. 2022; Shoji et al. 2022; Zhu et al. 2023). Polyvinyl alcohol fibre (PVA) has been widely used to reinforce ECC, as highlighted by Singh et al. (2019). Studies, such as the work of Tian and Zhang (2016), have delved into the utilisation of natural fibres in ECC. The literature extensively discusses the composition and ingredients of ECC, emphasizing its unique properties that can be customized by adjusting the formulation. Li and Li (2019) stress the importance of selecting materials and proportions for desired performance characteristics. Ma et al. (2015) focused on tailoring ECC with local ingredients for sustainability and cost reduction, exploring the effects of different mineral admixtures. Meng et al. (2017) specifically investigated the mechanical behaviour of PVA fibre-reinforced ECC using local ingredients, while Singh et al. (2019) conducted a comprehensive review on ECC's performance and composition analysis. Overall, ECC's composition involves careful selection and proportioning of materials, allowing for tailoring to achieve specific characteristics such as enhanced ductility, durability, and sustainability.

3. Mechanical Properties of ECC

3.1 Flexural Behaviour

Engineered Cementitious Composites (ECC) exhibit crucial flexural behaviour, featuring unique ductile qualities for substantial deformations and energy absorption without catastrophic failure (Nguyen and Lee, 2021). The incorporation of polymeric fibres enhances ECC's flexural strength, toughness, and crack resistance (Maalej and Li, 1994; Altwair et al. 2012; Qin et al. 2020; Ehrenbring et al. 2022; Liu et al. 2023). Factors like composition, fibre type, volume fraction, and loading conditions impact ECC's flexural behaviour, driving research towards optimization through alternative materials, fibre hybridization, and self-healing mechanisms. Additionally, Zhang and Li (2002) emphasized the role of fibre reinforcement in ECC's flexural behaviour and fatigue resistance in overlay systems (Fig. 1). This improved understanding supports ECC's application in durable structural elements, as highlighted in referenced studies. However, thorough evaluation of practical considerations such as cost and long-term durability is essential.

Özbay et al. (2013) examined ECC's self-healing capacity under sustained flexural loading, showcasing promising attributes for structure durability (Fig. 2). Pan et al. (2012) studied ECC composition's impact on flexural behaviour, emphasizing interactions among constituents and long-term performance. Studies by Zhu et al. (2012), Zhou et al. (2019), Halvaei et al. (2020), Pakravan et al. (2018), and Pakravan et al. (2016) explored various ECC flexural aspects, contributing to its optimization. Nguyen and Lee (2021) showcased ECC-high-strength steel composite beams, but practical considerations like cost and durability must be addressed. Altwair et al. (2012) emphasised alternative supplementary cementitious materials' benefits, needing thorough evaluation. Zhang and Li (2002) and Özbay et al. (2013) investigated fibre reinforcement and self-healing mechanisms, but long-term effectiveness warrants further study. Pan et al. (2012) delved into ECC composition, while other research offers insights into slag utilization, lightweight ECC development, and flexural strengthening, collectively enhancing ECC's flexural behaviour understanding. Further research is vital to evaluate long-term effectiveness in real-world applications.

3.2 Tensile Behaviour

Engineered Cementitious Composites (ECC) showcase exceptional tensile behaviour, attributed to their distinctive composition and microstructure. Their strain-hardening characteristic enables significant deformations and more effective stress distribution. The integration of short, discontinuous fibres enhances ECC's tensile strength, ductility, and crack resistance, with the matrix-fibre interface playing a crucial role in stress transfer and crack bridging. Research efforts focus on optimizing fibre type, content, and distribution for desired tensile properties. ECC's outstanding tensile behaviour makes it suitable for applications requiring high durability, crack control, and resistance to tensile forces, exemplified in Fig. 3 (Yang et al., 2014).

Numerous studies contribute to understanding ECC's tensile behaviour. Yu et al.'s (2018) review offers insights into direct tensile properties, emphasizing fibre-related influences. Yu et al. (2020a) explored size effects on tensile properties and compressive strength, underscoring specimen size's importance. Zhou et al. (2012) addressed fibre distribution and mechanical properties through mixing sequence adjustments. Wang and Li (2006) innovate high-early-strength ECC for enhanced tensile strength and durability. Tahmouresi et al. (2021) proposed a novel direct tensile strength evaluation, combining experimentation and numerical analysis. Wu et al. (2019) investigated natural sand morphological parameters, revealing insights into aggregate properties' role in tensile behaviour. Zhang and Zhang (2018) discussed matrix tailoring using low tensile strength PVA fibre, emphasizing optimizing matrix-fibre interaction for improved tensile behaviour.

While Chen et al. (2023) and Tian et al. (2022) explored ECC behaviour under dynamic and elevated temperature conditions and ECC-to-concrete bond interfaces, respectively, their findings may lack generalizability due to specific experimental setups or material compositions. Additionally, a more comprehensive consideration of real-world scenarios could enhance the practical relevance of their findings. Yu et al. (2020), Do et al. (2022), Ye et al. (2023), and Yu et al. (2023) contributed valuable insights into direct tensile properties, tension stiffening, size effects, and probabilistic-based investigations of ECC. However, a critical assessment of their methodologies and assumptions is warranted to ensure the validity and applicability of their models and findings across different ECC formulations and structural configurations. Saraireh et al. (2021) offered a unique perspective by examining the electro-mechanical tensile properties of ECC, but their study may benefit from further exploration of the interaction between mechanical and electrical stimuli on ECC behaviour, as well as the implications for its practical applications. Overall, while these studies significantly advance our understanding of ECC's tensile behaviour, a critical evaluation underscores the need for more comprehensive and standardized approaches, as well as a deeper consideration of real-world conditions and practical implications to enhance the utility and applicability of their findings in engineering practice.

3.3 Compressive Strength

Engineered Cementitious Composites (ECC) possess crucial compressive strength, typically high due to their dense microstructure and fine aggregates. Integration of materials like silica fume or fly ash boosts ECC's compressive strength, further fortified by short fibres for enhanced load transfer and crack resistance. Research targets optimal composition, mix design, and curing conditions to maximize ECC's compressive strength, ranging from 50 to 80 MPa. This places ECC among high-strength concrete materials without brittleness, making it ideal for robust and durable structural applications. Studies by Wang and Li (2006), Yu et al. (2020a), Sahmaran et al. (2010), and Ding et al. (2020) extensively explored ECC's compressive strength, offering insights into enhancement approaches, size effects, fire resilience, and predictive models.

Ajith et al. (2021) delved into mineral admixtures and manufactured sand's impact on ECC compressive strength, providing insights into material influences. Zhu et al. (2014) explored ductility's correlation with compressive strength in ECC using diverse binders like fly ash, slag, silica fume, and cement. Zhou et al. (2015) examined fibre-reinforced ECC's mechanical behaviour in uniaxial compression, emphasizing fibber reinforcement's role. Chung et al. (2018) analysed specimen shapes' effect on compressive strength, considering water-to-binder ratios and PVA fibre content. Other studies explored additional factors, such as Huang et al. (2013) investigating green lightweight ECC's mechanical and thermal properties. Yıldırım et al. (2015) studied compressive strength and autogenous shrinkage's effects on the bond behaviour of high-early-strength ECC, highlighting their interplay. Yu et al. (2020b) explored the feasibility of an ultrahigh-volume limestone-calcined clay blend for medium-strength ECC, aiming to enhance sustainability. Their study demonstrated the blend's potential to produce medium-strength ECC with desirable mechanical properties and improved sustainability, offering a promising approach to reduce the environmental impact of cement-based materials as can be seen in Fig. 4.

Huang et al. (2021) demonstrated engineered/strain-hardening cementitious composites (ECC/SHCC) with outstanding compressive strength exceeding 210 MPa (Fig. 5). Their study explored the materials' mechanical properties and strain-hardening behaviour, emphasizing potential applications for extensive deformations without failure. The research showcased the development of ECC/SHCC with ultra-high compressive strength, highlighting diverse engineering possibilities. The investigation underscores the potential for sustainable alternatives like limestone-calcined clay blends to create medium-strength ECC, enhancing overall sustainability in construction.

4. Durability properties of ECC

4.1 Chloride attack

Engineered Cementitious Composites (ECC) excel in resisting chloride ingress, vital for aggressive environments. ECC's unique microstructure and composition impede permeability, restricting chloride ion movement and minimizing steel reinforcement corrosion risk. Lepech and Li (2009) emphasized ECC's low water permeability. Sun et al. (2020) revealed ECC's excellent resistance to chloride diffusion under dry-wet cycles, promising prolonged durability. Li and Li (2011) highlighted ECC's self-healing capability, reducing potential chloride ingress pathways. Sun et al. (2022) and Shumuye et al. (2022) showed improved self-healing and chloride ingress resistance. Wang et al. (2023) affirmed ECC's sustained chloride resistance under continuous flexural loading, making it promising for structures requiring crucial chloride resistance. Figure 6 depicts a consistent decline in ECC's apparent chloride diffusion coefficients over time, attributed to microstructure densification and ongoing hydration, emphasizing ECC's substantial chloride ingress resistance.

4.2 Sulphate attack

Engineered Cementitious Composites (ECC) exhibit favourable behaviour in sulphate environments due to their unique composition and properties. In a study by Wang et al. (2020a), ECC displayed resilience in sulphate environments. Continuous ultrasonic measurements were employed to monitor and model damage evolution during sulphate attack. The study aimed to understand ECC's deterioration process and establish a reliable monitoring method for damage assessment. Sulphate exposure led to a gradual decrease in wave velocity and increased attenuation, as depicted in Fig. 7, indicating damage occurrence. The proposed damage evolution model, based on experimental data, offers quantitative insights into ECC's deterioration process, providing valuable tools for monitoring ECC structures in sulphate-rich environments.

Liu et al. (2017) conducted a comprehensive durability study on ECC in sulphate and chloride environments. Their research emphasizes the superior performance of ECC compared to traditional concrete in resisting sulphate attack. The typical tensile stress-strain relationship of ECC specimens under different exposure conditions are depicted in Fig. 8. The study demonstrates reduced expansion and deterioration of ECC in sulphate environments, highlighting its enhanced durability. ECC's low water permeability, dense matrix, and the presence of polymer fibres contribute to its ability to mitigate sulphate ingress.

Sridhar (2022) explored Engineered Cementitious Composites (ECC) durability with hybrid fibres, emphasizing their efficacy in resisting sulphate attack. Zhao et al. (2020) investigated ECC with high-volume fly ash and bentonite, revealing improved resistance to combined sulphate and freezing-thawing cycles. Incorporating hybrid fibres and these materials strengthens ECC, extending its service life in sulphate-rich environments. The studies provide valuable insights into ECC's superior resistance to sulphate attack, attributed to low water permeability, a dense matrix, and polymer fibres. Hybrid fibre reinforcement minimizes sulphate ion pathways, and additions like high-volume fly ash and bentonite further fortify ECC. Continuous ultrasonic measurements during sulphate attack enhance understanding and aid ECC formulation optimization for more durable structures in challenging conditions, positioning ECC as a superior material for infrastructure exposed to sulphate conditions over traditional concrete.

Baloch et al. (2023) investigated the effect of severe sulphate exposure on the bonding behaviour of hybrid engineered composite systems. Their findings shed light on the susceptibility of ECC to sulphate attack and underscore the importance of understanding bonding mechanisms in harsh environments. In a subsequent study, Baloch et al. (2024) explored the role of supplementary cementitious materials and fibre reinforcements in enhancing the sulphate attack resistance of Self-Consolidating Concrete (SCC)/ECC composite systems. Their research contributes valuable insights into strategies for improving ECC durability under sulphate exposure. Gou et al. (2023) focused on the durability development of lightweight and high-strength ECC subjected to combined sulphate-chloride attack under freeze-thaw cycles. By simulating real-world conditions, their study provides practical implications for ECC performance in aggressive environments. Abdulkadir et al. (2024) took a novel approach by optimizing sulphate and acid resistance in rubberized ECC with graphene oxide-pretreated crumb rubber. Their utilization of innovative materials and response surface methodology highlights the potential for enhancing ECC durability through advanced composite design. Collectively, these studies underscore the importance of considering sulphate attack resistance in the design and optimization of ECC systems, offering valuable insights and strategies for improving their durability in challenging environments.

4.3 Frost attack

Engineered Cementitious Composites (ECC) excel in frost resistance, making them ideal for freezing environments. ECC's high tensile ductility, low permeability, and enhanced crack control fortify its ability to endure freezing cycles. Its strain-hardening behaviour accommodates expansion and contraction without significant damage. ECC's self-healing capability repairs micro-cracks from frost action, enhancing its durability. Şahmaran and Li (2007) demonstrated ECC's superior resistance to de-icing salt scaling, crucial in cold regions (Fig. 9). Sahmaran et al. (2010) affirmed ECC's resistance to freezing-thawing cycles, showcasing minimal damage. Supplementary materials, as highlighted by Şahmaran et al. (2012), enhance ECC's frost resistance, reinforcing its suitability for frost-prone regions. Zhu et al. (2012) showcased ECC's autogenous self-healing during freeze-thaw cycles, ensuring long-term durability, while Zhao et al. (2020) found ECC's enhanced resistance to combined sulphate attack and freeze-thaw cycles, supporting its adaptability in aggressive frost and sulphate environments.

Wang et al. (2023) investigated the influence of frost damage on ECC performance, offering valuable insights into the material's response to freezing conditions. Their study provides a fundamental understanding of how frost affects ECC properties, contributing to the broader knowledge base on frost attack resistance. Gao et al. (2023) extended the investigation by examining the impact of low temperature and NaCl attack on ECC fracture properties. While their focus is not solely on frost attack, their findings shed light on ECC behaviour under cold and corrosive conditions, which are relevant to frost-prone environments. hao et al. (2020) studied the durability of ECCs containing high-volume fly ash and bentonite against the combined attack of sulphate and freezing-thawing (FT). Their research highlights the importance of considering multiple environmental stressors in assessing ECC performance, offering practical insights for frost-prone regions.

Bai et al. (2023b) and Liu et al. (2022) employed electrochemical impedance spectroscopy and mechanical strength modelling, respectively, to assess freeze-thaw damage in ECC. Their approaches provide innovative methods for evaluating frost attack resistance and offer new avenues for research in this area. Xie et al. (2021) investigated the effects of freeze-thaw damage on fracture properties and microstructure of hybrid fibre-reinforced cementitious composites containing calcium carbonate whisker. While not specific to ECC, their findings contribute to understanding frost-induced deterioration mechanisms in cementitious materials. Overall, the provided references collectively offer a thorough examination of ECC's frost attack resistance, employing various methodologies and considering multiple environmental factors. However, further research is warranted to develop comprehensive models and testing protocols specifically tailored to assess ECC performance in frost-prone conditions.

4.4 Other harsh environment

Engineered Cementitious Composites (ECC) showcase robust behaviour in challenging environments. Demonstrating resistance to acid attack, alkali-silica reaction, and high temperatures, ECC maintains structural integrity under elevated heat and possesses self-healing properties against alkali-silica reactions. Its low permeability ensures excellent resistance to seawater, and high flexural toughness combats abrasion and erosion. Nevertheless, ECC's behaviour varies based on mix design, curing, and fibre type. Ma et al. (2021) underscored ECC's overall durability, emphasizing mix design and curing effects. Wu et al. (2020) reveal ECC's resilience to acid mine drainage, while Wang et al. (2022) confirmed satisfactory resistance to chemical degradation and self-healing in simulated sewage environments. Şahmaran and Li (2008) showcased ECC's durability in highly alkaline conditions. Quan et al. (2021) exhibited enhanced corrosion resistance in ECC with supplementary materials under sulphate attack and dry-wet cycles.

The behaviour of ECC in harsh environments is a complex and multifaceted topic, as evidenced by the range of studies provided. Uğur et al. (2023) compared the effectiveness of blending and impregnation applications of dispersed nanoparticles on the performance of cementitious composites. While their study offers insights into enhancing the properties of cementitious materials, the direct applicability to ECC in harsh environments is not explicitly addressed. Hwalla et al. (2024) conducted a durability assessment of geopolymeric and cementitious composites for screed applications, providing valuable insights into the performance of alternative materials in harsh conditions. However, the specific focus on screed applications may limit the generalizability of their findings to other ECC applications.

Ouyang et al. (2023) investigated the effects of interface agent and cooling methods on the interfacial bonding performance of ECC and existing concrete exposed to high temperature. While their study addresses ECC's behaviour under elevated temperatures, the broader context of harsh environments, including chemical exposure or extreme weathering, is not fully explored.

Ma et al. (2023) studied the performances of fire-resistive ECCs, offering insights into ECC's behaviour under fire conditions. Their research contributes to understanding ECC's response to extreme heat, yet it does not encompass other harsh environmental factors that ECC may encounter. Shang et al. (2023) examined the interfacial fracture performance of ECC and fire-damaged concrete, shedding light on ECC's behaviour in post-fire scenarios. While their study addresses a specific aspect of harsh environments, the broader spectrum of environmental stressors is not thoroughly explored. Overall, while the provided references offer valuable insights into ECC's behaviour in various challenging conditions, there is a need for more comprehensive research addressing ECC's performance in a wider range of harsh environments, including chemical exposure, extreme temperatures, and severe weathering. Integrating findings from multiple studies could provide a more holistic understanding of ECC's durability and performance in harsh conditions.

5. Rheological Properties of ECC

5.1 Workability and Flowability

Engineered Cementitious Composites (ECC) excel in workability and flowability, surpassing conventional concrete. ECC's deformability allows significant tensile strain due to short fibres promoting strain distribution and crack resistance. Its flowability fills shapes and gaps without excessive vibration, useful in repair, retrofitting, and 3D printing. Şahmaran et al. (2013) optimized ECC workability by adjusting factors like water-cement ratio and superplasticizer dosage. Fischer & Shuxin (2003) emphasized mix design parameters and fibre roles in ECC flowability. Shanmugasundaram and Praveenkumar (2021) showed how supplementary materials enhance ECC's workability and flowability, stressing optimal curing conditions and mixing ratios.

Kim et al. (2007) explored ECC's tensile and fibre dispersion with blast furnace slag, noting improved workability. Wang et al. (2020b) found an optimal polyethylene fibre content positively influenced ECC's workability, enhancing cohesiveness. Subedi et al. (2021) noted raw sugarcane bagasse ash improved ECC's workability and flowability, enhancing mechanical properties. Wu et al. (2021) showed MgO-doped ECC improved workability, flowability, and mechanical properties. Bai et al. (2023a) optimized 3D printed ECC with recycled sand and polyethylene fibres, achieving desired workability. These studies underscore adjusting mix design parameters and incorporating supplementary materials to enhance ECC's workability for diverse construction applications.

5.2 Viscosity and Thixotropy

Viscosity and thixotropy are pivotal rheological traits shaping the workability and flow dynamics of Engineered Cementitious Composites (ECC). Viscosity, signifying internal flow resistance, plays a critical role in fibre dispersion and mechanical property enhancement. Strategic adjustments in factors like water-cement ratio, superplasticizers, and viscosity modifiers optimize ECC matrix viscosity, elevating mixtures' flow, uniformity, and workability. Conversely, thixotropy involves time-dependent viscosity reduction upon shearing, facilitating smoother material flow. Li and Li (2013) extensively examined ECC's rheology, fibre dispersion, and robustness, emphasizing viscosity control's paramount importance. Their analysis considers factors like water-cement ratio, superplasticizers, and viscosity modifiers, showcasing how optimizing viscosity enhances ECC's flow, homogeneity, and workability, ultimately fortifying its performance and durability. Rheological properties of seven ECC mixes are illustrated in Fig. 10.

Yang et al. (2009a) emphasized viscosity modifiers and superplasticizers' crucial role in controlling Engineered Cementitious Composites' (ECC) rheology, enhancing flow, stability, and pumpability during construction. Yücel et al. (2021) explored ECC with synthetic wollastonite microfibers, highlighting how higher aspect ratios improved thixotropic behaviour, enhancing flow, workability, and mechanical properties. Zhu et al. (2023) investigated a 3D-printable ECC cementation system, optimizing it for enhanced flow, printability, and structural integrity in additive manufacturing. Chen et al. (2020) focused on yield stress and thixotropy control in 3D-printed ECC with metakaolin, demonstrating improved flow, stability, and printing precision. These studies collectively underscore viscosity and thixotropy's crucial role in ECC's workability, offering nuanced insights for enhanced performance and durability in diverse applications.

5.3 Self-Healing and Crack Mitigation

Engineered Cementitious Composites (ECC) excel in the construction industry with unique self-healing and crack mitigation properties, enhancing durability and longevity. ECC's autonomous repair of microcracks is facilitated by internal healing agents like superabsorbent polymers or encapsulated healing agents. These agents react upon crack formation, forming new hydration products and sealing the cracks. This self-healing effectively mitigates crack propagation, preventing further damage and reducing maintenance requirements in infrastructure applications. Yang et al.'s (2011) investigation on ECC's autogenous healing during early curing stages emphasizes its substantial capability, demonstrated through crack closure, width reduction, and mechanical property recovery. Figure 11 showcases ECC's significant autogenous healing, highlighting its potential for mitigating crack damage and improving overall concrete structure durability.

The interaction between fibres and the cementitious matrix is crucial for promoting autogenous healing. Fibers create a network of reinforcement that hinders crack opening and provides a pathway for hydration products to fill the gaps. This mechanical interlocking effect contributes to the closure of cracks and the restoration of material integrity over time. Furthermore, fibres facilitate the transport of moisture and ions, accelerating the rehydration of un-hydrated cement particles near cracks. This accelerated hydration process promotes the formation of calcium silicate hydrate (C-S-H) gel, which fills microcracks and enhances the self-healing capacity of ECC. The type, aspect ratio, and dosage of fibres significantly influence autogenous healing performance. High aspect ratio fibres, such as steel or carbon fibres, exhibit superior crack bridging capability compared to low aspect ratio fibres. Additionally, optimizing the fibre dosage is essential to achieve a balance between mechanical strength and self-healing capacity.

Researchers, exemplified by Wu et al. (2012) and Ma et al. (2014), have explored the benefits of self-healing in ECC, noting advantages such as reduced water permeability, enhanced mechanical properties, and increased resistance to environmental factors like chloride attack. However, a critical analysis of the literature reveals challenges influenced by factors like crack width, material composition, and environmental conditions, significantly impacting ECC's self-healing capacity. Diverse approaches are evident, with studies focusing on autogenous healing mechanisms or exploring external agents and admixtures (Li & Li, 2011). Concerns about long-term stability, compatibility, and potential environmental impacts arise with the introduction of healing agents (Zhang et al., 2021). Yang et al.'s (2009b) research into ECC's self-healing rate under cyclic wetting and drying conditions, as shown in Fig. 12, underscores substantial autogenous healing, even in severe cycles. This emphasizes ECC's potential for self-repair in real-world environments experiencing moisture variations, highlighting its capacity to maintain structural integrity.

The reliability and broad applicability of self-healing in Engineered Cementitious Composites (ECC) require thorough exploration. Varied performances underscore the need for standardized protocols and comprehensive evaluation methods to ensure consistent behaviour (Sahmaran et al., 2015). Consistency is crucial for practical application, and long-term durability demands attention to factors like aging, cyclic loading, and real-life exposure, influencing ECC's extended healing performance and structural integrity (Özbay et al., 2013). Understanding self-healing ECC behaviour over time is vital, and practical implementation must consider cost-effectiveness, scalability, and compatibility with existing construction practices for widespread adoption (Kan et al., 2010). Successful integration promises to revolutionize the construction industry with heightened durability, sustainability, and resilience.

6. Fibre Reinforcement in ECC

Fibre reinforcement plays a crucial role in enhancing the mechanical properties and durability of ECC. The addition of fibres, such as polymeric or metallic fibres, improves the tensile strength, toughness, and crack resistance of ECC. These fibres act as a reinforcement network within the cementitious matrix, providing additional resistance against cracking and improving the post-cracking behaviour of the material. The fibre reinforcement effectively distributes stresses, reduces crack widths, and enhances the overall structural performance of ECC. Additionally, fibres contribute to the self-healing ability of ECC by bridging cracks and promoting the autogenous healing process. The incorporation of fibres in ECC significantly enhances its structural integrity and extends its service life.

6.1 Types Fibres and their effect on mechanical and structural properties of ECC

Engineered Cementitious Composites (ECC) can be enhanced with diverse fibres, including polymeric, metallic, and hybrid varieties, each offering unique benefits. Polymeric fibres like polyethylene and polypropylene enhance crack resistance and ECC durability. Metallic fibres, such as steel, provide high tensile strength for structural applications. Hybrid fibres, combining different types, yield synergistic effects, amalgamating varied benefits. The fibre selection depends on specific needs like mechanical properties, durability, and cost-effectiveness.

Numerous studies delve into the impact of fibre types on ECC. Lee et al. (2009) emphasized Polyvinyl Alcohol (PVA) fibre dispersion's importance. Maalej et al. (2012) reviewed hybrid fibre ECC for potential structural applications. Soe et al. (2013) explored new hybrid fibre ECC material properties, revealing positive influences. Pan et al. (2015) investigated cost-effective Polyvinyl Alcohol (PVA) engineered cementitious composites (PVA-ECC), underlining affordability and improved mechanics. Ma et al. (2015) tailored ECC with local ingredients, exploring fibre effects on workability, strength, and ductility. Pakravan et al. (2016) studied fibre hybridization effects using low- and high-modulus polymeric fibres, showing mechanical enhancement. Al-Gemeel et al. (2018) introduced hollow glass microspheres and hybrid fibres for improved ECC mechanics, promising lightweight and high-performance applications. Mohammed et al. (2018) optimized hybrid fibre combinations, achieving superior mechanics. Yu et al. (2020c) explored all-grade polyethylene fibre-reinforced ECC (PE-ECC), demonstrating enhanced seismic resistance. George et al. (2021) investigated various fibres like PVA, polypropylene, and steel, influencing ECC properties. Ismail and Hassan (2021) studied fibre type impact on ECC beam shear behaviour. These studies underline fibre reinforcement's ECC significance, offering potential for mechanical improvement, durability, and structural behaviour. Future research should explore synergistic fibre effects, optimizing content and distribution for specific ECC performance requirements.

6.2 Fibre Dispersion and Orientation in ECC

Fibre dispersion and orientation are pivotal factors influencing the mechanical properties and overall performance of Engineered Cementitious Composites (ECC). Lee et al. (2009) developed a technique to quantitatively assess polyvinyl alcohol (PVA) fibre dispersion in ECC, stressing the necessity of uniform distribution for effective crack bridging, heightened tensile and flexural strength, and improved mechanical behaviour. Proper fibre dispersion ensures even stress transfer across cracks, enhancing resistance to cracking. Yu et al. (2018) focused on ultra-high-performance ECC using polyethylene (PE) fibres, investigating fibre orientation's impact on properties. Controlling fibre alignment enhanced mechanical properties and durability, impacting ECC's anisotropic behaviour and resistance to crack propagation. Ge et al. (2021) explored extrusion methods on fibre orientation, finding it influenced ECC's mechanical properties. Proper fibre orientation during manufacturing allows tailoring ECC properties. Yu et al. (2021) emphasized fibre orientation control in 3D-printable ECC (3DP-ECC), crucial for achieving desired characteristics in additive manufacturing. These studies highlight the significance of optimizing fibre dispersion and orientation in ECC, offering opportunities for tailored material properties in diverse construction applications.

6.3 Synergistic effect

The incorporation of ECC creates a synergistic effect between the fibres and the cementitious matrix, enhancing the material's overall performance. Fibers act as mechanical reinforcements, bridging across microcracks to distribute stress and prevent crack propagation. This reinforcement mechanism significantly improves ECC's tensile strength, flexural performance, and resistance to structural failure under various loading conditions. Additionally, the interaction between fibres and the cementitious matrix enhances the material's cohesion and structural integrity, increasing its durability and resistance to environmental factors such as shrinkage and fatigue. Furthermore, the presence of fibres promotes autogenous healing within ECC, allowing the material to self-repair microcracks over time. This synergistic effect between fibres and the cementitious matrix makes ECC a versatile and sustainable material for a wide range of engineering applications, offering improved mechanical properties, enhanced durability, and long-term structural performance.

6.4 Means of enhancing bond between binder and fibre shapes

Enhancing the bond between binder and fibre shapes in ECC involves surface treatment of fibres, optimizing fibre morphology, controlling fibre orientation, adjusting mix design, incorporating admixtures, and ensuring proper curing conditions. Surface treatments modify fibre chemistry, promoting adhesion to the matrix. Optimizing fibre morphology and orientation enhances mechanical interlocking and alignment with stress directions. Adjusting mix proportions and using admixtures improve fibre dispersion and matrix cohesion. Proper curing conditions influence hydration kinetics, facilitating bond formation. Employing these means enhances ECC's mechanical properties, durability, and overall performance in structural applications.

Hossain et al. (2020) offered significant data on the bond strength of fibre-reinforced polymer bars, aiding in material selection for reinforcement. Qasim et al. (2022) provided practical implications for improving bond strength in hybrid ECC-concrete systems through experimental investigation. Tarabin et al. (2024) contributed to understanding bond behaviour in polyethylene ECC, considering various load conditions. Cai et al. (2020) deepen understanding of bond mechanisms in ECC and concrete, valuable for composite structural design. Wang et al. (2020c) contributed to comprehending ECC's behaviour under compression, vital for structural applications. However, further research is needed to explore the long-term durability and performance implications of enhanced bond strength in ECC.

Additionally, comparative studies between different reinforcement materials and loading conditions could provide comprehensive insights.

7. Applications of ECC

7.1 Structural Applications

Engineered Cementitious Composites (ECC) prove versatile in structural engineering, excelling in tensile strain, crack control, and durability. Ideal for bridge deck link slabs, ECC enhances longevity, addressing challenges like shrinkage and traffic loading. ECC's self-healing microcracks contribute to prolonged structural integrity. In seismic design, ECC's high ductility and energy dissipation improve resilience, crucial for interior beam-column connections. It finds utility in high-load structures and blast-resistant constructions. ECC aids repair, sealing cracks, and reinforcing structures. Its exceptional flexural and tensile properties suit thin elements like facade panels. ECC promotes sustainable construction by reducing maintenance, extending service life, and minimizing waste. Despite promise, further research is needed for optimization and cost challenges. Nonetheless, ECC stands as a versatile material for enhanced structural performance, durability, and sustainability.

Early recognition of ECC's potential came through Li and Kanda's (1998) innovations forum, highlighting its strain-hardening behaviour and crack control. Kim et al. (2004) focused on ECC's performance in bridge deck link slabs, showcasing its effectiveness in crack control and service life extension. Maalej et al.'s (2012) comprehensive review of hybrid fibre ECC emphasized its versatility and ability to enhance structural performance through improved crack control and increased ductility. Qudah and Maalej's (2014) investigation into Engineered Cementitious Composites (ECC) for interior beam-column connections revealed ECC's ability to enhance seismic resistance by mitigating damage during seismic events. Emphasizing ECC's energy dissipation and self-healing properties, the study showcased its potential to reduce vulnerability to earthquakes, contributing valuable insights for seismic resilience.

To emulate the intricate multi-level stratification observed in natural materials like mother of pearl, researchers devised a bio-inspired stacked beam configuration. This setup introduces artificial zones for connection and separation between layers, akin to the mineral bridges, tablet interlocking, and nano-asperities found in nacre layers. Through this approach, it was illustrated that a multilayered design coupled with weakened interfacial connections can prompt interlamellar sliding, fostering both local and overall strain alleviation. Consequently, this enhances ductility while maintaining strength, as depicted in Figure 13 and Figure 14 (Ye et al., 2021).

Ding et al. (2022) conducted a comprehensive review on high-strength ECC (HS-ECC), emphasizing its design, mechanical properties, and structural applications. The research highlighted HS-ECC's potential in demanding structural elements where strength, durability, and crack control are crucial, advancing understanding in this specialized area. Deng et al. (2023) focused on sustainable ultra-lightweight ECC, emphasizing material characterization and design optimization to balance reduced weight with enhanced mechanical properties. The study explored the potential benefits of ultra-lightweight ECC in reducing environmental impact while maintaining structural integrity. Poongodi et al. (2022) provided a review on ECC's performance in structural applications, covering mechanical properties, durability, and crack control. Their work consolidated knowledge on ECC's effectiveness in enhancing structural performance, highlighting areas for further exploration. Collectively, these studies underscore ECC's diverse structural applications, from seismic resilience to sustainability, while emphasizing the need for ongoing research to optimize performance and address challenges for widespread implementation in structural engineering practice.

Zhou et al. (2023) conducted the flexural test using the MTS Exceed E45 electronic universal testing machine. The displacement loading was applied to the centre of the specimens at a rate of 0.1 mm/min, with a span of 100 mm, as depicted in Fig. 15. Load–deflection curves for ECC425 and ECC525 specimens are illustrated in Fig. 16, denoting ordinary Portland cement P.O 42.5R and P.O 52.5R, respectively. Both curves exhibit three stages: elastic, strain hardening, and failure. During the elastic stage, ECC525 specimens displayed a slightly higher Young's modulus due to the superior grade cement used. Initial crack strength and ultimate strength were similar for both ECC types, calculated via the three-point bending strength formula. As specimens entered the strain hardening stage, bearing capacity increased with fluctuations attributed to emerging tiny cracks. In the failure stage, accompanied by extensive cracking, bearing capacity fluctuated before reaching maximum mid-span deflection. Despite comparable maximum deflection, ECC525 specimens showed higher initial crack strength and ultimate strength compared to ECC425, suggesting the significant contribution of cement base material strength to ECC mechanical properties.

7.2 Sustainable and Green Building Practices

Engineered Cementitious Composites (ECC) embody sustainability in construction, utilizing industrial by-products like fly ash and slag in production to reduce resource usage and waste. ECC's crack control and durability extend service life, reducing replacements and associated environmental impact. Its energy-efficient properties stabilize indoor temperatures, reducing reliance on mechanical systems and lowering energy consumption and carbon emissions. ECC's self-healing minimizes waste by autonomously repairing micro-cracks, promoting a circular economy. Lower water requirements conserve water, and enhanced crack control prevents structural deterioration, reducing water-intensive maintenance. ECC's durability and seismic resistance enhance resilience, minimizing environmental and economic impacts. Life Cycle Assessment studies validate ECC's environmentally friendly profile, supporting a sustainable built environment with reduced environmental impact, energy efficiency, waste reduction, water conservation, and enhanced resilience.

8. Challenges and Limitations of ECC

8.1 Cost and Availability

Engineered Cementitious Composites (ECC) encounter challenges related to cost and availability in the construction industry. Despite ECC's acknowledged superior mechanical properties, crack control, and durability, the inclusion of specialized materials such as high-strength fibres and chemical admixtures elevates production costs compared to traditional concrete. Procuring high-quality cement, fine aggregates, and fibres contributes to increased expenses, and the need for specific equipment and skilled labour further amplifies costs. Limited access to ECC materials and technologies regionally exacerbates these challenges, hindering widespread adoption.

Addressing these issues involves ongoing research focusing on ECC formulation optimization, exploring cost-effective fibre types, and refining manufacturing techniques. Standardization processes and education initiatives play key roles in enhancing ECC availability, fostering industry standards and guidelines, and promoting broader understanding. A comprehensive, multifaceted approach encompassing research, standardization, education, and industry collaboration is necessary to overcome ECC's cost and availability limitations and make it a more feasible option for construction projects with its unique advantages in performance, durability, and sustainability.

8.2 Standardisation and Code Regulations

Standardization and code regulations play a crucial role in integrating Engineered Cementitious Composites (ECC) into the construction industry. These frameworks ensure ECC materials, production processes, and applications adhere to specific criteria, enhancing quality control and promoting consistent performance. Technical specifications, test methods, and performance criteria are developed, covering material composition, mixing proportions, manufacturing procedures, and performance testing. These standards form the basis for quality assurance, facilitate product comparisons, and encourage ECC's acceptance in construction projects. Standardization harmonizes practices across regions, fostering collaboration and knowledge sharing.

Code regulations govern ECC application in building codes, outlining requirements for structural elements, repair, retrofitting, and sustainable building practices. They ensure ECC structures meet safety and durability standards, providing a legal framework for architects, engineers, and contractors to confidently incorporate ECC while complying with regulations. Developed by industry organizations and governmental bodies, these regulations reflect current best practices and ECC technology advancements, evolving to address emerging challenges and sustainability considerations. Implementing standardized ECC practices and adhering to code regulations ensures consistent material quality, structural integrity, safety, and interoperability, instilling confidence in investors, owners, and regulatory bodies and promoting ECC's broader acceptance and adoption in construction projects.

9. Future Trends and Research Directions

The future trajectory of Engineered Cementitious Composites (ECC) research is marked by a concerted effort to enhance their self-healing and crack mitigation capabilities. An essential focus involves a deeper exploration of the self-healing mechanisms within ECC, with an emphasis on understanding the roles of microorganisms, bio-based materials, and bio-mineralization processes. Advanced characterization techniques, such as X-ray tomography and acoustic emission monitoring, are pivotal in providing nuanced insights into the self-healing processes of ECC at different scales, contributing to a more comprehensive understanding of its mechanisms and performance.

Another crucial facet of future ECC research revolves around standardization and testing protocols. The establishment of consistent and reliable methodologies for evaluating ECC's self-healing performance is paramount. This standardization not only facilitates accurate comparisons between different ECC formulations but also serves as a foundational step towards the seamless integration of self-healing technologies into practical construction applications. Additionally, a forward-looking perspective encompasses the comprehensive evaluation and prediction of ECC's long-term durability, investigating the effects of aging, cyclic loading, and exposure to adverse environments to develop robust predictive models and design guidelines. The integration of ECC with sustainable practices, the exploration of smart materials, and addressing real-world challenges further underscore the dynamic and promising future of ECC in the construction industry.

10. Concluding Remarks

Engineered Cementitious Composites (ECC) have emerged as a promising material with remarkable self-healing and crack mitigation capabilities. The research conducted so far has provided valuable insights into the mechanisms, benefits, and challenges associated with ECC's self-healing properties. ECC offers the potential for reduced water permeability, improved mechanical properties, and enhanced resistance to environmental factors such as chloride attack. However, certain limitations and challenges remain, including the need for standardized testing protocols, a better understanding of long-term durability, and practical implementation considerations. To unlock the full potential of ECC, future research should focus on enhancing self-healing mechanisms, developing advanced characterization techniques, establishing standardized testing protocols, assessing long-term durability, promoting sustainability, integrating with smart materials, and addressing practical implementation challenges. By addressing these research directions, ECC can pave the way for more durable, resilient, and sustainable structures in the construction industry. With ongoing advancements and a comprehensive understanding of ECC's self-healing capabilities, this material has the potential to revolutionise the way we design and construct infrastructure, leading to safer, more reliable and longer-lasting built environments.

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