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Composition of Engineered Cementitious Composite with Local Materials, Composite Properties and Its Utilization for Structures in Developing Countries †

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Abstract: This study focuses on developing cost-efficient engineered cementitious composites (ECCs) with glass and polypropylene fibers, using local materials for sustainable construction in developing countries. The ECC exhibits unique properties such as strain hardening, enhancing structural resilience and crack mitigation. The composite utilizes 1–2% volume of 6mm fibers, with fly ash as a supplementary cementitious material and a superplasticizer. The PPGF-ECC surpasses PC in mechanical properties, making it suitable for various applications, including rigid pavements in developing countries. This research recommends 2% PPGF-ECC for various applications in developing countries, including rigid pavements, due to its superior performance.

Keywords: material; engineered cementitious composite (ECC); pseudo ductility; durability; volume stability; structural applications

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1. Introduction

Concrete, primarily composed of cement, has inherent limitations like low tensile strength and ductility, although it boasts high compressive strength. The addition of synthetic and polymer fibers in specific ratios can significantly enhance its ductility [1]. Engineered cementitious composite (ECC), a fiber-reinforced material, displays unique strain-hardening behavior, maintaining small fracture widths (<100 μm) under tension stress and offering remarkable ductility and strength through meticulous micromechanical design [2]. ECC, specifically, exhibits high tensile strength, resilience and the ability to self-heal small cracks when exposed to water and air [3,4]. Under tensile and bending loads, ECC dissipates energy effectively and creates numerous fine fractures [5–7].

ECC often uses local materials for sustainability in large-scale projects. Germany, Brazil and China have experimented with regional materials and local PVA fibers, facing challenges in mechanical properties and cost. Exploring affordable fiber alternatives is crucial to mitigate PVA fiber costs [8]. In developing countries, balancing performance and cost when choosing construction materials is crucial. ECC's high unit cost, largely driven by PVA or PE fiber expenses, has hindered its widespread adoption. Many efforts have been made to replace costly PVA fibers with more affordable synthetic options like PE, PP and PAN fibers [9]. Wang et al. [10] suggest that substituting PVA with PP fibers can result in cost savings for fibers. In developing countries, an alternate to the high-cost fiber material will lead to the sustainable development of ECC as a construction material.

ECC finds applications in three distinct types of infrastructure: building, transportation and water resources. Various qualities of the ECC material are employed to address specific issues within each of these infrastructure categories [11]. This research focuses on ECC adoption in developed nations and aims to facilitate its production in developing countries.

It aims to create a ductile composite using glass and PP fibers, exploring composite behavior, micro-mechanical design, materials and practical applications in infrastructure projects. The findings can assist developing nations in addressing infrastructure challenges with ECC.

2. ECC Criteria's and Properties

2.1. ECC Micromechanics

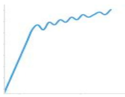
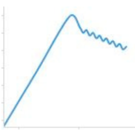
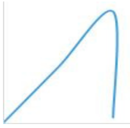
To ensure the initiation of cracks at multiple points, it is crucial that the maximum fiber-bridging strength exceeds the matrix rupture strength. Additionally, the complementary energy provided by the bridging fiber should surpass the peak crack toughness to maintain steady-state multiple cracking. These requirements are defined in the ECC pseudo strain hardening criteria [3,12,13].

2.2. ECC Properties

ECC's strain-hardening is due to steady-state flat cracks under sustained loading. To maintain this, ECC needs ample energy exceeding fracture toughness and tensile strength surpassing fiber-bridging strength, allowing cracks to start from different points, leading to steady-state cracking [5,7,10,12].

Table 1 summarizes ECC's and FRC's properties, including fracture pattern, material behavior, strength and deformation. An ideal ECC exhibits closely spaced cracks, strain-hardening, high strength and significant deformation capacity, showcasing its superiority [14]. Conversely, in moderate- to low-quality ECC composites, the transition occurs from multiple spaced fractures towards single crack formation, exhibiting pseudo ductile behavior with high strength [15,16]. In contrast, typical FRC materials feature a single, prominent crack and limited ductile failure characteristics and do not possess the high strength and deformation capabilities observed in ECC [17].

Table 1. Properties used to characterize ECC and FRC composites.

S. No	Composite	Fracture Pattern	Composite Behavior	Graphical Image	High Strength	High Deformation	Ref
1	Ideal ECC	Multiple close cracks 	Strain hardening		✓	✓	[2]
2	ECC	Multiple spaced cracks 	Pseudo ductile		✓	✓	[15]
3	Acceptable ECC or HPFRCC	Single crack 	Pseudo ductile		✓	✓	[16,17]
4	FRC	Single crack 	Low ductility		✗	✗	[18]
5	PC	Broken in two pieces 	Brittle		✗	✗	[18]

3. Materials and Employed Methodology

3.1. Materials and Specimen Preparation

The materials utilized include OPC cement, sand, fly ash (Class-F), Polycarboxylate-based superplasticizer (SP) and portable water, supplemented with synthetic polymer fibers. Commercially available glass and polypropylene fibers were both employed, each with a 6 mm length [19,20].

3.2. Mix Design, Manufacturing, Casting and Specimens

For ECC preparation, a ratio of 1:0.8:1.2 (cement:sand:fly ash) was used [5,7]. Multiple ECC batches were created, incorporating polymer fiber percentages of 1%, 1.5% and 2% by volume to examine the impact of increased fiber content [21]. These fibers consisted of a blend of glass and polypropylene, each contributing half of the specified percentage in their respective batches [5]. The fly ash content remained consistent across all batches, with Class F fly ash used, and sand added per the specified ratio [7,22]. A Poly-carboxylate-based superplasticizer, at 1.2% of the binder material's weight, was added for workability [5]. To achieve higher strength, the water–cement ratio was set at 0.30 for the engineered cementitious composite, while a 0.55 water–cement ratio was used for PC. The specimens, including cylinders and slabs, were cast, demolded after 24 h and cured for 28 days. Slab specimens comprised those with steel bars, with longitudinal bars and without steel, totaling 12 slabs specimens and 12 cylinders, with 3 representing PCC and 3 representing 2% PPGF-ECC for each mechanical test.

3.3. Testing

3.3.1. Procedures for Mechanical Properties

The compressive strengths of both PCC and ECC were determined using a Universal Testing Machine (UTM). The ASTM C39 test was applied to cylindrical specimens of PC and the bendable composite with a 200 mm diameter and 400 mm height. The Splitting-Tensile test, following ASTM C496M-02 standards, was conducted using the same UTM machine, with both PC and bendable composite cylinders undergoing the testing procedure.

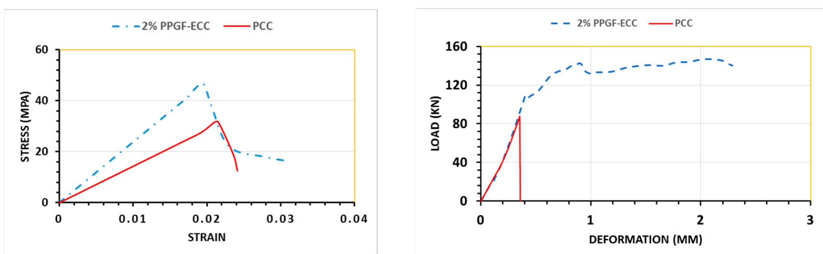
3.3.2. Test Setup for Flexural Capacity of Slabs

Flexural testing was conducted following the ASTM C78 criteria, utilizing a three-point loading system, with a deflection loading rate of 0.5 mm/s. This testing procedure was applied to both PC and ECC composite slabs. The slab dimensions were a length of 457 mm, a width of 203 mm and a height of 50 mm.

4. Results

4.1. Composite Properties of PC and ECC

Upon analyzing the test results, it became clear that among PPGF-ECC and PC, the PPGF-ECC displayed the highest compressive strength (C-S) value. Notably, the compressive strength of 2% PPGF-ECC exhibited a significant increase of 45%, presented in Figure 1a. The 2% PPGF-ECC achieved the highest (STS) value, which could be attributed to a potentially ideal volume percentage of polypropylene and glass fibers shown in Figure 1b.



(a) (b)

Figure 1. (**a**) Compressive behavior; (**b**) split tensile behavior.

4.2. Flexural Behaviour of Slabs with PC and ECC

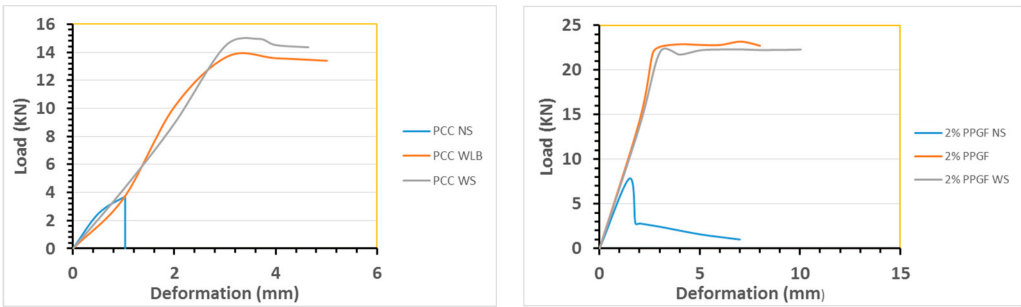
The highest F-S value was achieved by the 2% PPGF-ECC, potentially owing to an optimal percentage of fiber content bridging the matrix. Regarding the flexure behavior of the PC and PPGF-ECC composites, the PC composite presented brittle behavior as the graph directly fell, while the PPGF-ECC presented pseudo ductile behavior after the peak load. Figure 2 presents the cracking pattern of PPGF-ECC. A single large crack with a few multiple cracks was observed after the testing of the specimens. The composite exhibited certain properties of ECC; therefore, it was characterized as HPFRCC [16, 17].

(**a**) (**b**)

Figure 2. Cracking of 2% PPGF-ECC composite: (**a**) Slab 1; (**b**) Slab 2.

4.2.1. Load Deflection Curves

The load deflection curves of the slab specimens of PC and PPGF-ECC are presented in Figure 2. The slab specimens consisted of those with steel (WS), with longitudinal bars (WLB) and with no steel (NS). When comparing Figure 3a,b, the bridging effect of fibers after the peak load could be observed, with a gentle downward curve of load and ultimate deflection in the PPGF composite, while the PC composite exhibited a sudden downturn after the peak load. The F-S of PPGF was also enhanced as compared to PC. PPGF composites with steel and with longitudinal bars exhibited greater F-S and toughness compared to the RCC composite.



(**a**) (**b**)

Figure 3. Flexural behavior of slabs: (**a**) PC slabs; (**b**) PPGF-ECC slabs.

4.2.2. Flexural Capacity

Table 2 presents the results for different mechanical tests. The testing included compressive strength, spitting tensile strength and flexural strength. PPGF-ECC exhibited better flexural capacity in terms of flexural strength, deformation and toughness index. Figure 3 presents the cracking induced in PPGF flexural specimens. Multiple cracks with single large cracks were observed. Multiple cracks enhanced post the peak performance of PPGF-ECC.

Table 2. Mechanical properties of PPGF-ECC and PC.

Composite	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
PC NS	25	1.5	2.2
2% PPGF NS	41	2.8	4.7

5. Conclusions

This research aimed to develop ECC using local materials and assess its mechanical performance in comparison to PC. The goal was to showcase ECC as a durable and sustainable option for use in developing countries. ECC samples with 2% fiber content, comprising 1% PP and 1% G fibers, were analyzed, yielding the following results:

- PPGF-ECC exhibited notable mechanical property improvements compared to PC, including higher strength, increased energy absorption pre and post peak and enhanced toughness, demonstrating its superior performance.
- Remarkably, the 2% PPGF-ECC showed a significant 45% increase in compressive strength and enhanced toughness, along with the highest STS and F-S values, compared to PCCs C-S, STS and F-S.
- PC was brittle with a sudden graph drop in the flexural test, whereas PPGF-ECC exhibited pseudo ductility after the peak load. PPGF-ECC displayed a cracking pattern with a single large crack and a few small multiple cracks, while the specimen of PCC broke with single large cracks, presenting the brittle nature of the composite.

ECC's superior mechanical properties, elongation and durability make it a suitable choice for development in developing countries. PPGF-ECC composites' utilization in structural elements will result in durable and sustainable construction in developing countries.

6. Possible Practical Application

Moreover, ECC has potential to be used in rigid pavement, but further studies should be conducted in this regard for the validation of the composite durability.

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References

1. Lu, C.; Hao, Z.; Chu, H.; Lu, Z. Investigation on performance of engineered cementitious composites (ECC) based on surface modification of PET fibers using graphene oxide (GO) and polydopamine (PDA). *Constr. Build. Mater.* **2023**, *368*, 130343. [CrossRef]
2. Zhang, K.; Yuan, Q.; Huang, T.; Zuo, S.; Yao, H. Utilization of novel stranded steel fiber to enhance fiber–matrix interface of cementitious composites. *Constr. Build. Mater.* **2023**, *369*, 130525. [CrossRef]
3. Li, J.; Qiu, J.; Weng, J.; Yang, E.H. Micromechanics of engineered cementitious composites (ECC): A critical review and new insights. *Constr. Build. Mater.* **2023**, *362*, 129765. [CrossRef]
4. Shoji, D.; Ogwezi, B.; Li, V.C. Bendable concrete in construction: Material selection case studies. *Constr. Build. Mater.* **2022**, *349*, 128710. [CrossRef]
5. Zhou, H.; Wu, J.; Wang, X.; Chen, Y.; Du, X.; Yu, S. Performance of engineered cementitious composite (ecc) monolithic and composite slabs subjected to near-field blast. *Eng. Struct.* **2023**, *11*, 279. [CrossRef]
6. Chen, M.; Wang, Y.; Zhang, T.; Zhang, M. Behaviour of structural engineered cementitious composites under dynamic tensile loading and elevated temperatures. *Eng. Struct.* **2023**, *280*, 115739. [CrossRef]
7. Hao, Z.; Lu, C.; Li, Z. Highly accurate and automatic semantic segmentation of multiple cracks in engineered cementitious composites (ECC) under dual pre-modification deep-learning strategy. *Cem. Concr. Res.* **2023**, *165*, 107066. [CrossRef]
8. Kakooei, S.; Akil, H.M.; Jamshidi, M.; Rouhi, J. The effects of polypropylene fibers on the properties of reinforced concrete structures. *Constr. Build. Mater.* **2012**, *27*, 73–77. [CrossRef]

9. Tan, Y.; Zhao, B.; Yu, J.; Xiao, H.; Long, X.; Meng, J. Effect of cementitious capillary crystalline waterproofing materials on the mechanical and impermeability properties of engineered cementitious composites with microscopic analysis. *Polymers* **2023**, *15*, 1013. [CrossRef]
10. Wang, T.; Zhang, D.; Zhu, H.; Ma, B.; Li, V.C. Durability and self-healing of engineered cementitious composites exposed to simulated sewage environments. *Cem. Concr. Compos.* **2022**, *129*, 104500. [CrossRef]
11. Deng, B.Y.; Li, L.Z.; Tan, D.; Uddin, M.N.; Cai, Z.W.; Yu, K.Q. Sustainable and cost-effective ultra-lightweight engineered cementitious composite: Design and material characterization. *Cem. Concr. Compos.* **2023**, *136*, 104895. [CrossRef]
12. Yu, K.; Lin, M.; Tian, L.; Ding, Y. Long-term stable and sustainable high-strength engineered cementitious composite incorporating limestone powder. *Structures* **2023**, *47*, 530–543. [CrossRef]
13. Şahmaran, M.; Özbay, E.; Yücel, H.E.; Lachemi, M.; Li, V.C. Frost resistance and microstructure of engineered cementitious composites: Influence of fly ash and micro poly-vinyl-alcohol fiber. *Cem. Concr. Compos.* **2012**, *2*, 156–165. [CrossRef]
14. Huang, B.T.; Zhu, J.X.; Weng, K.F.; Li, V.C.; Dai, J.G. Ultra-high-strength engineered/strain-hardening cementitious composites (ECC/SHCC): Material design and effect of fiber hybridization. *Cem. Concr. Compos.* **2022**, *129*, 104464. [CrossRef]
15. Qian, S.; Zhou, J.; De Rooij, M.R.; Schlangen, E.; Ye, G.; Van Breugel, K. Self-healing behavior of strain hardening cementitious composites. *Cem. Concr. Compos.* **2009**, *31*, 613–621. [CrossRef]
16. Arain, M.F.; Wang, M.; Chen, J.; Zhang, H. Study on PVA fiber surface modification for strain-hardening. *Constr. Build. Mater.* **2019**, *197*, 107–116. [CrossRef]
17. Hanif Khan, M.; Zhu, H.; Ali Sikandar, M.; Zamin, B.; Ahmad, M.; Muayad Sabri Sabri, M. Effects of Various Mineral Admixtures and Fibrillated Polypropylene Fibers on the Properties of Engineered Cementitious Composite (ECC) Based Mortars. *Materials* **2022**, *15*, 2280. [CrossRef]
18. Hussain, T.; Ali, M. Improving the impact resistance and dynamic properties of jute fiber reinforced concrete for rebars design by considering tension zone of FRC. *Constr. Build. Mater.* **2019**, *213*, 592–607. [CrossRef]
19. Khan, M.; Ali, M. Use of glass and nylon fibers in concrete for controlling early age micro cracking in bridge decks. *Constr. Build. Mater.* **2016**, *125*, 800–808. [CrossRef]
20. Khan, M.; Ali, M. Effectiveness of hair and wave polypropylene fibers for concrete roads. *Constr. Build. Mater.* **2018**, *166*, 581–591. [CrossRef]
21. Zhu, B.; Pan, J.; Zhang, M.; Leung, C.K. Predicting the strain-hardening behaviour of polyethylene fibre reinforced engineered cementitious composites accounting for fibre-matrix interaction. *Cem. Concr. Compos.* **2022**, *134*, 104770. [CrossRef]
22. Li, V.C.; Horikoshi, T.; Ogawa, A.; Torigoe, S.; Saito, T. Micromechanics-based durability study of polyvinyl alcohol engineered cementitious composite. *Mater. J.* **2018**, *3*, 242–248.