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Optimizing Workability in Engineered Cementitious Composites

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***Abstract*—Engineered Cementitious Composites (ECC) draw attention in the construction industry owing to excellent tensile behaviour, ductility, and self-healing capabilities. Usage of secondary cementitious materials make ECC a sustainable construction composite. Fibers used in ECC impart enhanced flexural performance making it a versatile material across varied applications. Although ECC exhibits excellent mechanical properties, it imposes few challenges in achieving a workable mix. This paper experiments on fresh properties of ECC giving due importance to mixing procedure. Evaluation of factors influencing workability and influence of mixing techniques, constituent materials on workability and compressive strength is carried out. Results indicated that mixes from planetary mixers exhibited superior slump flow and compressive strength in comparison with mixes from pan mixers. Hand held mixers produced mixes with comparable slump flow and compressive strength to those from planetary mixers. Ground Granulated Blast Furnace Slag (GGBS) content beyond 50% resulted in lower compressive strength and lesser workable mixes.**

***Keywords*— Engineered Cementitious Composites (ECC), Mixing Techniques, Workability, Compressive Strength, GGBS.**

I. INTRODUCTION

Engineered Cementitious Composites have emerged as a prominent material in the construction industry due to their outstanding mechanical properties, including high tensile strength, ductility, and superior self-healing capabilities. These unique characteristics make ECC a sustainable alternative to traditional concrete, particularly in structural and infrastructural applications. The use of secondary cementitious materials, such as fly ash or slag, further enhances the sustainability of ECC by reducing the reliance on ordinary Portland cement, which contributes to reducing the carbon footprint of concrete production. Additionally, the inclusion of fibers in ECC significantly improves its flexural performance, enabling applications that demand enhanced durability and toughness, such as bridges, tunnels, and earthquake-resistant structures.

Despite these advantages, ECC faces certain challenges, particularly in achieving a workable mix that retains its desirable mechanical properties. The high fiber content, required for the composite's enhanced performance, tends to reduce the fluidity of the mix, complicating the workability of ECC. Inadequate workability can lead to issues such as uneven distribution of fibers, reduced bonding between the matrix and reinforcement, and an overall decrease in the material's mechanical properties. Therefore, addressing the workability of ECC is critical for ensuring consistent and reliable performance in practical applications.

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The significance of improving ECC workability extends beyond material performance, as enhanced workability contributes to the practical feasibility of using ECC in large-scale construction projects. Achieving optimal workability ensures better processing, reduced labor costs, and improved construction efficiency, thereby facilitating the widespread adoption of ECC in structural applications.
This paper focuses on the investigation of the fresh properties of ECC, with particular emphasis on the mixing procedure and its influence on workability. The study aims to identify key factors that affect the workability of ECC, such as water-binder ratio, super plasticizer dosage, mixing methods and the type of cementitious materials used. Understanding these influencing factors is essential to establish a clear relationship between workability and the mechanical properties of ECC. By evaluating these correlations, this research provides valuable insights into optimizing the mix design of ECC for improved performance and broader applicability.

II. LITERATURE REVIEW

The potential use of large amounts of Class-F fly ash (55% and 70% cement substitution) and locally accessible mortar sand (MS) in place of silica sand (SS) in ECC was investigated (Sherir et al., 2018). ECC, known for its high strain capacity and improved durability, was assessed for properties such as slump flow, strengths, drying shrinkage, and frost resistance. Replacing SS with MS reduced slump flow but had minimal impact on strength and bending capacity, while reducing drying shrinkage and expansion by up to 30%. The findings confirm the feasibility of using MS in ECC mixtures for sustainable and cost-effective construction.
The mechanical and fresh properties of waste rubber used as a partial substitute for silica sand in self-consolidating engineered cementitious composites (SCECC) were examined (Ismail et al., 2018). Rubber type (powder and crumb rubber), rubber content (0–50%), and additional cementing materials (metakaolin, fly ash, slag, and silica fume) were all examined in relation to SCECC characteristics. Results showed that crumb rubber (CR) negatively impacted fresh and mechanical properties, but up to 30% CR could achieve strengths over 40 MPa. Powder rubber (PR) performed better, allowing up to 40% replacement. Combining PR with SCMs, especially metakaolin, enabled higher rubber content for sustainable, semi-lightweight SCECC with adequate properties for structural use.
The impact of two types of PVA fibers on the mechanical and physical properties of different ECC mixes was examined for Slump, density, compression, flexural, split tensile, and ductility (M. I. Khan et al., 2017). Three ECC mixes, with and without coarse aggregates, were studied, using varying fiber dosages (0%, 0.5%, 1%, 1.5%, and 2%). Slump, density, compression, flexural, split tensile, and ductility tests were conducted. Results showed that workability decreased with increasing fiber content but remained within acceptable limits up to 2%. Coarse aggregates reduced ductility, but strain-hardening and cracking behavior were maintained. Mechanical properties improved with up to 1.5% fiber content, with 1.5% found to be the optimal dosage.
ECC’s fresh properties using fly ash and blast furnace slag in mortar mixes with varying fly ash-to-slag ratios were tested, focusing on flowability and rheological behavior (Abdelaziz et al., 2019). Experimental results on flowability and flowability loss are presented and discussed. The results showed a direct proportional relation between the number of blows (the external applied stress) and the instant flowability of mortar.
Investigation on rheological control to optimize the fresh properties of ECC for improved mechanical performance considering four factors—fly ash ratio, water-binder (W/B) ratio, high-range water reducer, and viscosity-modifying admixture was studied(Yang et al., 2009). Results showed that the water-binder ratio significantly affects plastic viscosity, influencing tensile strength and strain capacity. Marsh cone and mini-slump flow tests were effective in assessing ECC rheological properties, aiding in producing self-consolidating ECC with optimized fiber distribution and micromechanical design.
Impact of W/B ratios, mineral admixtures, and local sand types on the tensile ductility of ECC using white and red dune sands, with their sieved forms, sourced from the Arabian Desert was examined (M. I. Khan et al., 2017). Fly ash (FA) and GGBS were used as mineral admixtures. ECC mixtures with GGBFS showed increased ductility over time, while FA-based mixtures saw a reduction. A 62% GGBFS mix with a W/B ratio of 0.35 achieved the best properties, with a 4.2% strain capacity and 5.2 MPa tensile strength at 28 days. Dune sand-based ECC performed comparably to silica sand-based ECC.
The impact of water-binder (w/b), sand-binder (s/b), superplasticizer-binder (SP/b) ratios, and maximum aggregate size (Dmax) on ECC properties using regression models and multi-objective optimization was investigated (Yang et al., 2009). Results show that w/b, s/b, and SP/b ratios significantly influence workability and mechanical properties, while Dmax has little effect.
The influence of different mixer types—pan, handheld, and planetary—on the properties of Engineered Cementitious Composites (ECC) was examined, with attention to flowability, compressive strength, elasticity,

tensile behavior, flexural performance, and fiber dispersion (Cai et al., 2024). The study found only slight variations in flowability, compressive strength, and elastic modulus among the mixers. However, notable differences were observed in tensile strength, with pan mixers exhibiting a performance reduction of up to 72.25%. Despite this, all mixer types maintained satisfactory flexural strength, while planetary mixers demonstrated the most uniform fiber distribution and consistent pore structure. Another study investigated how various mixing procedures and mixer types affect the fresh and hardened properties of concrete, considering factors such as mixer type, mixing duration, speed, timing of superplasticizer addition, and air pressure within the mixing pan (Dils et al., 2012). The results indicated that high-intensity mixers can significantly reduce the required mixing time. Introducing a stabilization period was found to be effective in determining optimal mixing time and achieving desired workability. Moreover, delaying the addition of the superplasticizer notably enhanced workability, particularly in mixes with a low water-to-cement ratio. The use of vacuum mixing also contributed to improved overall concrete performance. Effect of mixing on the performance of macro synthetic fiber-reinforced concrete was showcased using Single-fiber pull-out tests on fibers in their original and mixed states, alongside flexural tests to analyse the impact of mixing time and mixer type (Lerch et al., 2018). Results show that mixing improves the performance of flat fibers, while crimped or embossed fibers remain unaffected. Prolonged mixing times (over 10 minutes) in a pan mixer adversely affect performance, whereas tilting drum mixers maintain performance even after 60 minutes of mixing.

A practical mix design for ECC, a high-performance FRCC featuring strain-hardening and multiple-cracking behavior was developed (Fischer et al., 2003). The ECC studied incorporates 2% PVA fibers and aims to retain workability and mechanical properties while being mixed in conventional gravity-based drum mixers instead of specialized laboratory mixers.

The study outlines strategies for achieving a flowable, self-consolidating ECC mix suitable for large-scale applications. These include optimizing the particle size distribution and chemical composition of the matrix, refining mixing sequences and intervals, and leveraging common cement types and chemical admixtures. A case study demonstrates the viability of these approaches, bridging the gap between laboratory-scale and field-scale production.

The impact of two types of polyvinyl alcohol (PVA) fibers on the mechanical and physical properties of ECC was investigated (S. W. Khan et al., 2023). To address the high cost of ECC without compromising tensile performance, three ECC mix types (with and without coarse aggregate) were tested with varying fiber content by volume (0%, 0.5%, 1%, 1.5%, and 2%). Slump, density, compression, flexure, split tensile, and ductility tests were conducted on fresh and hardened specimens. Results showed that workability decreased with increasing fiber content but remained within ASTM limits up to 2%. The inclusion of coarse aggregate reduced the ductility of ECC but preserved strain-hardening and multiple-cracking behavior. Mechanical properties (compressive, tensile, and flexural strengths) improved with fiber content up to 1.5%, which was identified as the optimal dosage. Fiber content beyond 1.5% led to a slight decline in mechanical performance for all mixes.

III. OBJECTIVES

- To optimize the water binder ratio for binary blended ECC incorporating Ordinary Portland cement (OPC) and GGBS
- To arrive at optimum dosage of chemical admixtures for each binary mix
- To evaluate the effect of different mixing techniques/ equipment on workability of ECC.
- To examine the effect of various type of mixers and constituent materials on compressive strength.

IV. MATERIALS AND MIX PROPORTIONS

A. Materials and mixers used

Binder: OPC 53 grade affirming to recommendation of IS 12269:2013 was considered for the study.

Secondary Cementitious material: GGBS with Specific gravity of 2.85 is used for the study.

Fine Aggregates: 12.5 mm graded manufactured sand is used as fine aggregates.

Fibers: PVA fibers of bunchy monofilament type having density of 1.29 with length 6-12 mm are used for the study.

Chemical Admixture: Sulphonated naphthalene polymers based High performance super plasticising admixture with specific gravity 1.18 BS 5075, BS: EN 934-2 and with ASTM C494 was used.

Mixers Used: Three different mixers are used namely Pan Mixer, Handheld mixer, Planetary mixer for the experimental study. They are graphically represented in Fig 1 (Cai et al., 2024).

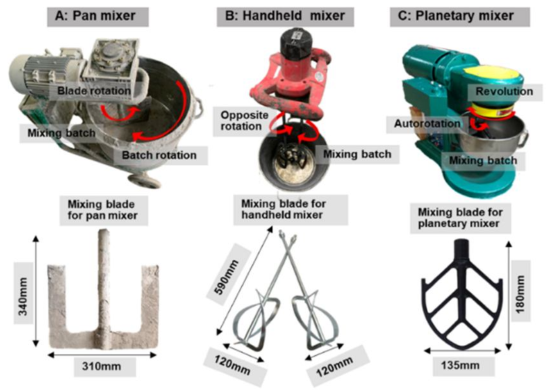

Fig 1 Graphical representation of mixers used in the study (Cai et al., 2024)

B. Mix Composition used in the study

TABLE I MIX COMPOSITION OF VARIOUS MIXES

Mix Designation	Binders	w/b ratio	Sand to OPC ratio	Volume of fibres (%)	Superplasticizer dosage (%)
M1	70%OPC + 30%GGBS	0.27	0.8	0.50	1.00
M2	60%OPC + 40%GGBS	0.285	0.8		0.90
M3	50%OPC + 50%GGBS	0.29	0.8		0.90
M4	40%OPC + 60%GGBS	0.29	0.8		0.85
M5	70%OPC + 30%GGBS	0.27	0.8	1.00	1.00
M6	60%OPC + 40%GGBS	0.29	0.8		0.90
M7	50%OPC + 50%GGBS	0.31	0.8		0.90
M8	40%OPC + 60%GGBS	0.31	0.8		0.85
M9	70%OPC + 30%GGBS	0.26	0.8	1.50	1.00
M10	60%OPC + 40%GGBS	0.29	0.8		0.90
M11	50%OPC + 50%GGBS	0.31	0.8		0.90
M12	40%OPC + 60%GGBS	0.30	0.8		0.85
M13	70%OPC + 30%GGBS	0.26	0.8	2.00	1.00
M14	60%OPC + 40%GGBS	0.295	0.8		0.90
M15	50%OPC + 50%GGBS	0.316	0.8		0.90
M16	40%OPC + 60%GGBS	0.27	0.8		0.85

V. METHODOLOGY ADOPTED

The methodology adopted for the study focuses on the optimization of water to binder ratio, chemical admixture dosage and appropriate mixing method and equipment to achieve a workable ECC mix. The study also correlates the workability with compressive strength of ECC mixes. Fig 2 presents the methodology adopted in the study.

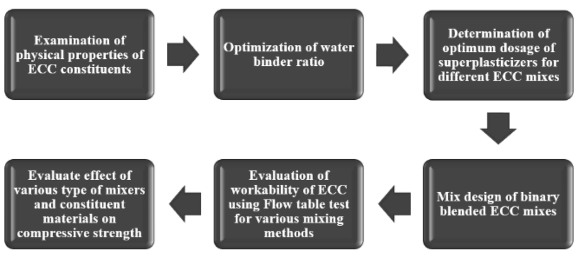

Fig 2 Methodology

VI. RESULTS AND DISCUSSIONS

A. Properties of ECC constituents

The physical properties of ECC constituents, including the binder, fibers, aggregates, and admixtures, are tailored to improve workability, durability, and crack resistance, crucial for the high-performance nature of ECC. The properties of various ECC constituents are tabulated in Table 2, Table 3, and Table 4.

TABLE II. PHYSICAL PROPERTIES OF OPC53

Property	**Value**
Compressive Strength (3 Days)	27 MPa
Compressive Strength (7 Days)	37 MPa (min)
Compressive Strength (28 Days)	53 MPa
Initial Setting Time	30 Minutes
Final Setting Time	600 Minutes
Fineness	225 m^2/kg
Soundness	10 mm
Bulk Density	1440 - 1460 kg/m^3
Specific Gravity	3.20

TABLE III. CHARACTERIZATION OF GGBS

Characteristics	Values (As provided by the supplier)
Fineness(m^2/kg)	440
Loss on ignition (%)	0.24
Insoluble Residue (%)	0.36
Calcium Oxide (%)	37.40
Magnesia Content (%)	6.80
Sulphide Sulphur (%)	0.26
Sulphite Content (%)	0.37
Manganese Content (%)	0.15
Chloride Content (%)	0.028
Glass Content (%)	94.5

TABLE IV. PROPERTIES OF SUPERPLASTICIZER

Characteristics	**Values (As provided by the supplier)**
Specific gravity	1.2
Type	Sulphonated Napthalene Polymers based
Chloride Content	Zero
Appearance	Brown to dark brown
pH	5.5-7.5

B. Standard Consistency Test

This test helps to establish the correct water-to-cement ratio for preparing cement paste, mortar, or concrete. It ensures the mix has adequate workability without being too fluid or stiff. The results are tabulated in Table 5.

TABLE V. STANDARD CONSISTENCY OF VARIOUS MIXES

Binders	Standard Consistency (w/b ratio)
70%OPC + 30%GGBS	0.29
60%OPC + 40%GGBS	0.31
50%OPC + 50%GGBS	0.34
40%OPC + 60%GGBS	0.35

C. Marsh Cone Test

To achieve at optimum dosage of chemical admixture with binders, marsh cone test was conducted. Total of 4 mixes are used for the experimentation with varying GGBS content. Sulphonated Napthalene polymers based high performance super plasticising admixture was used as chemical admixtures. The results of march cone test are tabulated in Table 6.

TABLE VI MARSH CONE TEST RESULTS

Mix	Optimum dosage of Superplasticizer (sp/b %)
70%OPC + 30%GGBS	1.00
60%OPC + 40%GGBS	0.90
50%OPC + 50%GGBS	0.90
40%OPC + 60%GGBS	0.85

D. Slump Flow

The slump flow test evaluates the horizontal flowability of ECC without any external obstructions. It assesses the material’s ability to spread under its own weight, ensuring it can adequately fill formwork without the aid of vibration, all while retaining a uniform and homogenous composition. The slump flow test results of various mixes under different mixing methods are shown in Table 7 and Fig 3.

TABLE VII. SLUMP FLOW OF ECC MIXES

Mix Designation	Slump Flow, mm		
	Pan Mixer	Handheld mixer	Planetary Mixer
M1	567	598	630
M2	636	672	706
M3	626	662	695
M4	546	578	607
M5	535	567	595
M6	600	636	668
M7	592	627	658
M8	516	546	573
M9	506	536	563
M10	568	602	632
M11	558	592	620
M12	488	516	542
M13	486	514	540
M14	545	578	606
M15	538	569	598
M16	468	496	520

Results indicated that increased fiber volume reduces slump flow across all binder compositions and mixer types, indicating lower workability. Higher GGBS content decreases slump flow, suggesting reduced workability as GGBS increases. Planetary mixers produced the highest slump flow, indicating better mixing efficiency. Handheld mixers showed intermediate values. PAN mixers gave the lowest slump flow values.

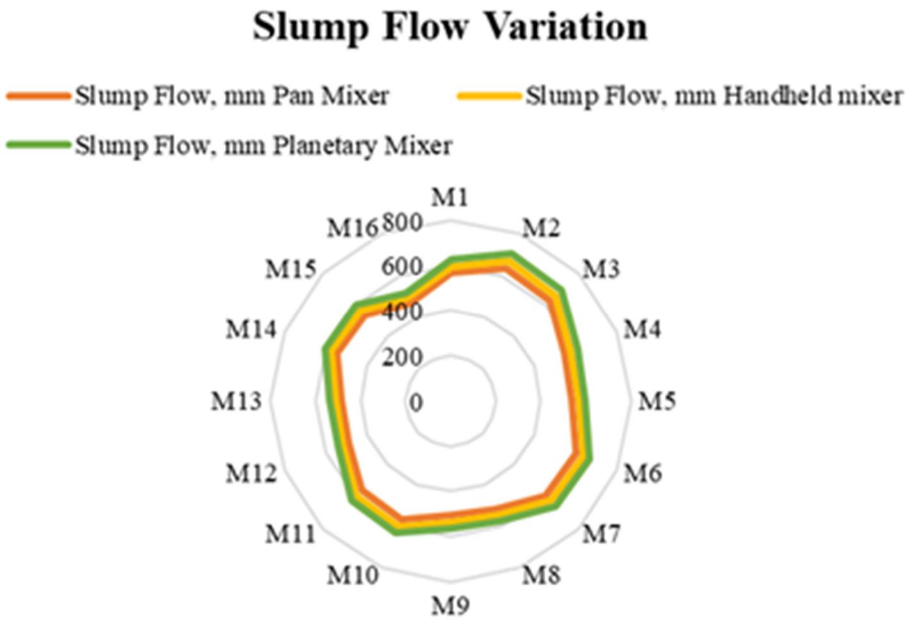

Fig 3 Slump Flow Variation in different mixers

E. Compressive strength test

Findings of the compressive strength test are shown in Table 8 and Fig 4. The results indicated that compressive strength increases progressively from Pan Mixer to Handheld Mixer to Planetary Mixer. This indicates better compaction and uniformity achieved with more efficient mixers such as planetary mixers. Mixes with higher fiber volumes (M9, M10, M13) generally show higher compressive strength, likely due to improved crack-bridging effects provided by the fibers. Higher GGBS proportions (M3, M4, M7, M8, M12) tend to reduce compressive strength compared to mixes with higher OPC content. This is due to slower strength development associated with GGBS. Mix M13 showcasing the strongest performance with balanced OPC and GGBS ratios and high fiber volume. Mix M4 due to high GGBS content and lower binder reactivity.

TABLE VIII. 28-DAY COMPRESSIVE STRENGTH TEST RESULTS

Mix Designation	Compressive Strength, MPa		
	Pan Mixer	Handheld mixer	Planetary Mixer
M1	54	56	58
M2	50	53	55
M3	44	46	48
M4	34	36	37
M5	56	59	62
M6	54	57	59
M7	44	46	48
M8	35	37	39
M9	58	61	64
M10	55	58	60
M11	50	53	55
M12	41	43	45
M13	60	63	66
M14	56	59	62
M15	51	54	56
M16	44	46	48

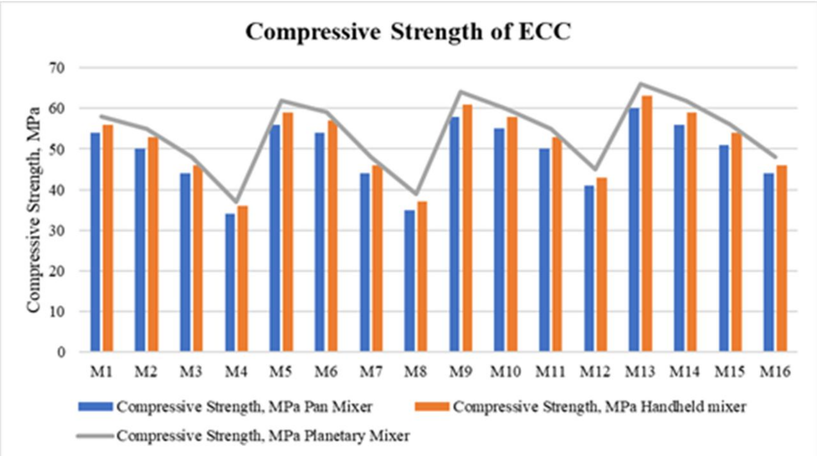

Fig 4 Compressive strength Variation in different mixers

VII. CONCLUSION

- Variations in Slump flow is in the range of 5-10% across various mixing techniques/mixers. Planetary mixers induce highest slump flow and pan mixers induce 90% slump flow to that of planetary mixers. Slump flow decreases with Increasing fiber volume, Increasing GGBS percentage. GGBS upto 50% replacement level exhibit satisfactory slump flow for highway applications (450–600 mm). Beyond this replacement level, ECC becomes less workable.
- Similarly compressive strength variation is upto 10% with mixes from Planetary mixers resulting in highest compressive strength and that from Pan mixers showcase lowest strength. Increasing fiber content enhances compressive strength whereas increase in GGBS content decreased compressive strength. Beyond 50% replacement level, the compressive strength drastically reduces. This is attributed to insufficient alkali activators resulting in unreacted GGBS and subsequently lower compressive strength.

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