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Sustainable Cementitious Composites with Epoxy–Alccofine Synergy

Rajendra Ganapati Hegde[1,*], K. G. Guptha[2]

Abstract

This research examines the combined influence of epoxy resin and Alccofine when used as partial substitutes for cement in producing sustainable, high-performance concrete. The study aims to improve both strength and durability properties while simultaneously reducing cement usage and its environmental impact. Concrete mixes were prepared with epoxy resin contents of 0%, 5%, and 10% by weight of cement, along with Alccofine replacement levels of 5%, 10%, and 15%. The experimental program involved assessing compressive strength, split tensile strength, and flexural strength at curing periods of 7, 28, and 56 days. Additionally, durability performance was evaluated through tests on water absorption, resistance to acidic environments, and rapid chloride permeability to understand long-term behavior under aggressive exposure conditions.-The results indicated that the mix containing 5% epoxy resin and 10% Alccofine exhibited the most balanced performance across both strength and durability parameters. This optimum combination resulted in an increase of approximately 24% in compressive strength and 18% in flexural strength compared to the control mix, along with a significant reduction in water absorption, indicating improved matrix densification and reduced porosity. Microstructural analysis using Scanning Electron Microscopy (SEM) confirmed the formation of a denser and more homogeneous internal structure. This improvement is attributed to the combined effect of Alccofine-induced pozzolanic reactions, which contribute additional calcium silicate hydrate (C–S–H) formation, and the polymeric film-forming characteristics of epoxy resin, which enhance particle bonding and reduce micro crack propagation. Overall, the study shows that the combined use of epoxy resin and Alccofine can significantly improve the mechanical performance and durability of concrete. The findings highlight the potential of such hybrid cementitious systems in developing sustainable construction materials with enhanced resistance to chemical attack and improved long-term structural performance, aligning with the objectives of eco-efficient and resource-optimized construction practices.

Keywords: Epoxy resin, alccofine, hybrid concrete, mechanical strength, durability, microstructure, SEM analysis

***Author for Correspondence**
Rajendra Ganapati Hegde
E-mail: rghhegde@gmail.com

[1]Research Scholar, Department of Civil Engineering, Goa College of Engineering (Affiliated to Goa University), Ponda, Goa, India
[2]Retired Professor, Department of Civil Engineering, Goa College of Engineering (Affiliated to Goa University), Ponda, Goa, India

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INTRODUCTION

Grouts, polymers, and epoxies have significantly contributed to overcoming the limitations of conventional cement-based systems in recent decades [1]. Ordinary Portland cement, in isolation, exhibits limitations in resisting environmental degradation, chemical attacks, such as acids and alkalis, and in meeting specialized requirements related to surface finish and curing performance [2]. In this context, polymer mortar or resin mortar – comprising cementitious binders combined with liquid resins or monomers in the absence of water – has emerged as a viable alternative material system [3]. Epoxy resins, typically formulated as two-component systems, are widely employed as substitutes or modifiers within polymeric resin systems [4, 5]. The performance efficiency of polymers and epoxies is strongly dependent on parameters such as cement type, epoxy monomer chemistry, curing agents, solvents, and resin composition [6].

A considerable body of research has been directed toward improving concrete performance through particle packing optimization using conventional cementitious systems and by incorporating supplementary cementitious materials (SCMs) as partial cement replacements. Studies have also explored the influence of polymers and epoxy-based modifications on concrete and micro-concrete systems [7, 8]. In addition, investigations have been carried out on epoxy systems, including water–miscible epoxy formulations, for enhancing concrete performance [4, 9]. It has been established that proper control of particle size distribution (PSD) significantly influences critical concrete properties such as workability, density, and hydration kinetics. Furthermore, optimization of PSD has been shown to improve compressive strength while simultaneously reducing water demand [10, 11]. These findings highlight the importance of understanding aggregate packing behaviour for achieving enhanced concrete performance [12].

The incorporation of supplementary cementitious materials (SCMs) in concrete has also been widely studied by several researchers. Extensive investigations have demonstrated the effectiveness of SCMs such as silica fume, ground granulated blast furnace slag (GGBS), and fly ash as partial cement replacements [7, 8, 13, 14]. While these materials contribute positively to rheological properties, permeability reduction, and strength enhancement, certain practical limitations have been reported [15, 16]. In particular, reduced workability due to particle angularity and surface roughness presents challenges in field applications. Nevertheless, these studies collectively advance the understanding of optimizing concrete mixtures through judicious use of SCMs [17].

Further research on polymer- and epoxy-modified concrete has provided detailed insights into their influence on fresh and hardened properties [18–20]. Such modifications have been shown to improve workability, compressive strength, impermeability, and durability characteristics. However, environmental concerns related to toxicity and volatile organic compound (VOC) emissions have driven the development of more sustainable water-based epoxy systems [5]. These studies collectively emphasize the need to balance performance enhancement with environmental sustainability in polymer- and epoxy-modified concrete systems [21].

Additional studies on epoxy-modified concrete have reported significant improvements in mechanical strength, durability, and deformation behavior [5, 22, 23]. Innovative applications, including prefabricated reinforced components and self-healing systems utilizing epoxy resins, have further expanded the scope of epoxy applications in concrete technology. These investigations highlight the broad potential of epoxy modification across diverse construction scenarios. Overall, existing research underscores multiple approaches to concrete enhancement involving particle size optimization, SCM incorporation, and polymer/epoxy modification. However, a research gap persists in the combined use of micro-fine cement systems with water–miscible epoxy formulations, particularly in micro-concrete applications.

Despite extensive literature on polymer-modified concrete and SCM-based systems, no comprehensive studies have investigated the combined effect of micro-fine cement (Alccofine 1108) and water–miscible epoxy systems (EL-Monobond-200®). The ultra-fine particle size of Alccofine (approximately 5–6 microns) enhances pozzolanic reactivity and densification of the matrix, while water–miscible epoxy is expected to chemically integrate with the hydration process. This synergistic combination remains largely unexplored, particularly with respect to workability, strength development, and durability performance in micro-concrete systems [24–26]. The present study addresses this research gap through a systematic evaluation of the physical, mechanical, and durability properties of micro-concrete incorporating Alccofine 1108 and EL-Monobond-200®.

A further research gap exists in the absence of studies evaluating micro-cement systems in combination with water–miscible epoxy as a cementitious modification approach [8]. The planned experimental investigations aim to bridge this gap and provide deeper insights into the behavior of such hybrid systems. Epoxy-modified concrete, which continues to evolve through advanced formulations and optimized property enhancement, represents a promising construction material [25–27]. The observed improvements in compressive strength, durability, and self-curing characteristics further support its applicability in repair and retrofitting works, particularly in inaccessible locations where conventional curing practices are difficult to implement.

MATERIALS AND METHODOLOGY

Materials

Ordinary Portland Cement (OPC) of 43 grade manufactured by ACC, conforming to IS 8112:1989, was used in this study [28]. Micro-fine OPC, commercially known as Alccofine 1108, having a Blaine fineness greater than 8000 cm²/g and manufactured by Alcon Micro Fines, conforming to IS 16993, was also incorporated as a supplementary cementitious material. EL-Monobond 200®, a two-component water–miscible epoxy system manufactured by Krishna Conchem, was used as the polymer modifier. The material conforms to the relevant IS provisions, and its detailed properties, as provided in the manufacturer's Technical Data Sheet (TDS), are included as Annexure-A.

Fine aggregate in the form of standard sand (TAMIN make), conforming to IS 650 and comprising three standardized grading zones, was used throughout the experimental program. The physical and mechanical properties of the binders used in this study are presented in Tables 1 and 2. Similarly, the physical properties of aggregates are summarized in Table 3. In addition, the particle size distribution of all binder materials considered in this study is presented in Figure 1.

Table 1. Physical properties of binders.

Property	OPC	Alccofine
Grade	53	1203
Specific gravity	3.15	2.91
Particle size	90 Microns	5–6 Microns
Fineness	2277 g/cm^2	1187 g/cm^2
Bulk density	1449 kg/m^3	680 kg/m^3

Table 2. Chemical properties of binders.

Constituents	OPC	Alccofine
	Compositions (%)	
SiO_2	21.95	34.57
CaO	63.86	32.89
Al_2O_3	5.98	22.05
MgO	3.11	7.98
Fe_2O_3	3.18	1.43
SO_3	1.56	0.57
Na_2O	0.36	0.51

Table 3. Physical properties of aggregates.

Property	FA	CA
Specific gravity	2.68	2.74
Water Absorption	1.12%	0.11%
Zone	Zone – II	–
Bulk density	1701 kg/m^3	1605 kg/m^3

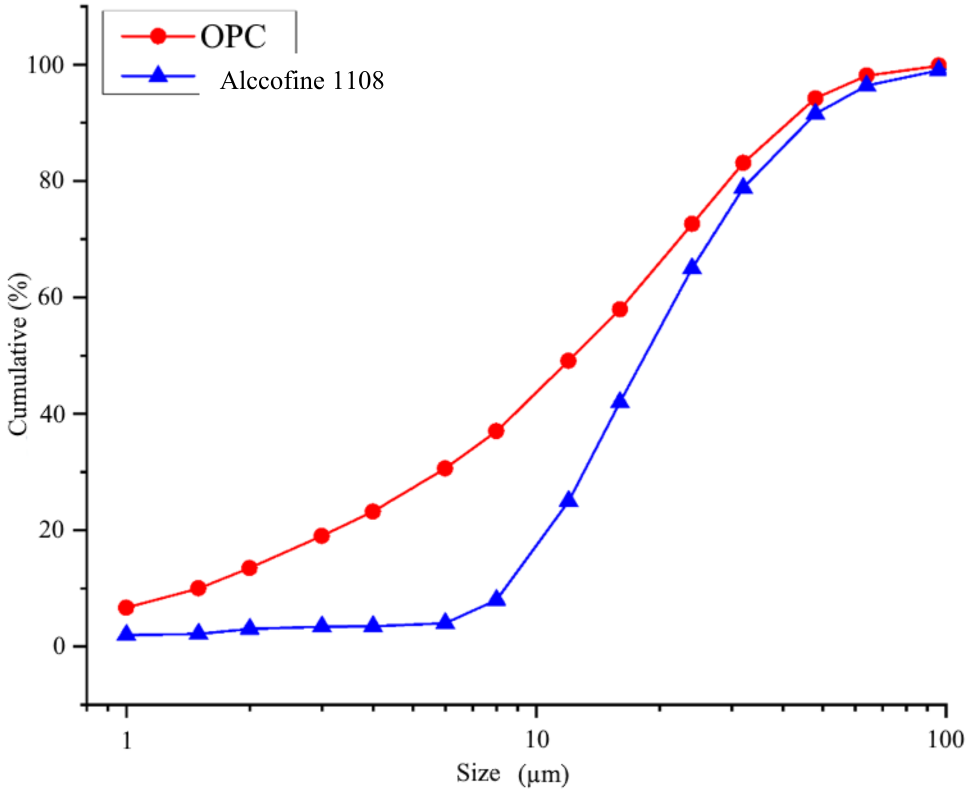

Figure 1. Particle size distribution of binders.

Methodology

Standard specimens conforming to IS 4031 (Part 6) were cast for the experimental investigation. In addition, cube specimens of size 50 × 50 × 50 mm were prepared, taking into consideration the size effect, and the results were interpreted in accordance with the provisions of IS 456:2000.

Control specimens prepared using Ordinary Portland Cement were compared with specimens cast using micro-fine cement and epoxy EL-Monobond 200®. Further comparative studies were extended to include other epoxy formulations to evaluate performance variations. Flow value, which is widely accepted in literature for its reliability and rationality in assessing workability, was adopted as the primary evaluation parameter.

Since EL-Monobond 200® is a water–miscible epoxy system, its compatibility with cementitious materials was examined through controlled dilution. Epoxy was incorporated as a percentage by weight of cement, and a systematic nomenclature was developed to represent the varying dilution levels. Initially, the dilution range was maintained between 0.5 and 2.0 times the weight of cement. Subsequently, the dilution range was extended from 2.0 to 2.5 and beyond, based on considerations of workability performance and economic feasibility.

The following nomenclature was adopted for specimen identification:

- *NMC:* Normal micro-concrete with Ordinary Portland Cement.
- *EPNC:* Epoxy-modified micro-concrete with Ordinary Portland Cement.
- *MMC:* Micro-concrete with Micro-fine cement.
- *EPMC:* Epoxy-modified micro-concrete with Micro-fine cement.

The above classification provides a clear framework for specimen identification, ensuring systematic comparison of experimental results and improving the coherence and reproducibility of the study.

RESULTS AND DISCUSSIONS

The study covers the evaluation properties under three categories: viz., Physical, Mechanical, and Durability.

Physical Properties

The assessment of physical properties included a comprehensive evaluation of weight, density, surface appearance, colour, ease of handling, and workability at varying epoxy dosages. The results have been systematically organized for clarity and ease of interpretation. Table 3 presents the physical properties observed in specimens prepared using normal OPC, while Table 4 provides the corresponding physical characteristics of specimens incorporating Alccofine 1108 micro-fine OPC. Furthermore, Figure 1 and Table 5 illustrate the working range of epoxy-modified concrete at different epoxy content levels. Figure 1 visually represents the influence of varying epoxy percentages on the physical behaviour of the concrete, demonstrating the corresponding changes in workability and related properties. This structured presentation facilitates a clear understanding of the dependence of physical properties on epoxy content and enhances the overall interpretability of the experimental observations.

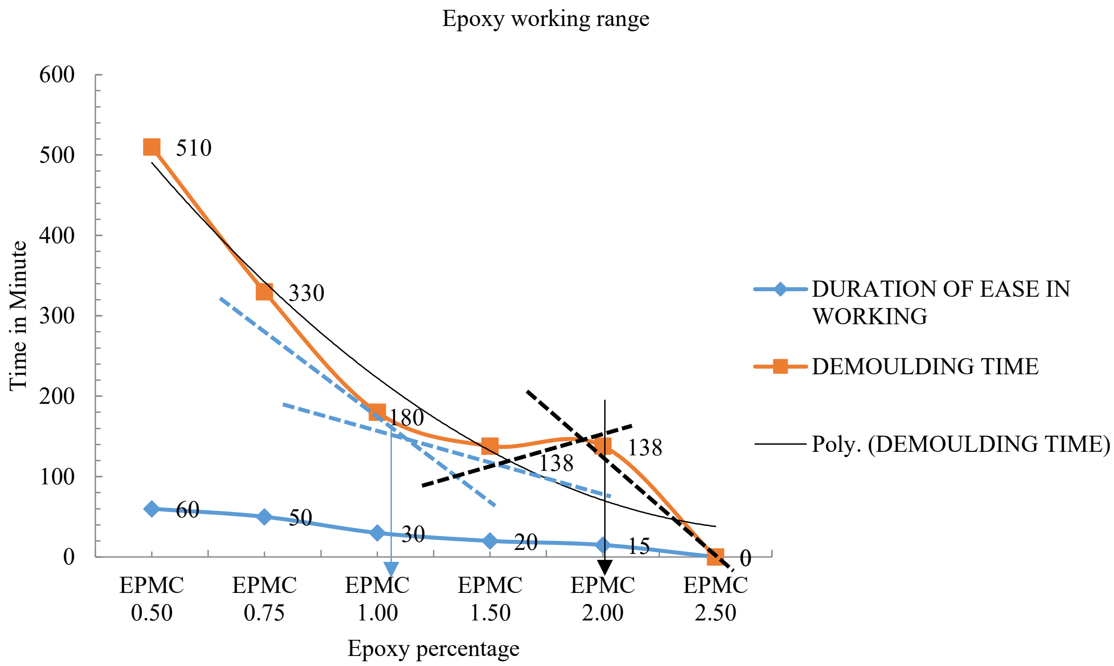

Figure 1. Working range of epoxy.

Mechanical Properties

Mechanical properties, including compressive strength, split tensile strength, and flexural strength, along with the influence of epoxy dilution on workability, were systematically evaluated. The test results are presented in Table 6, which is divided into two parts, namely Part A corresponding to Ordinary Portland Cement and Part B corresponding to Alccofine 1108 micro-fine OPC. In addition, the graphical representation of the mechanical properties of the test specimens is provided in Figures 2 and 3, illustrating the comparative performance trends across different mixes. Further, durability-related and supplementary mechanical property tests were carried out on the optimized combination of epoxy with Alccofine 1108 to assess its enhanced performance characteristics. These results serve as a reference baseline for comparison with normal OPC-based concrete systems. The structured presentation of results in this manner enhances clarity and enables a comprehensive understanding of the variations in mechanical behaviour associated with Ordinary Portland Cement and Alccofine 1108 modified systems.

Table 6. Mechanical properties.

Specimen size (mm)	Sample ID	Epoxy–cement ratio (%)	Compressive strength N/mm^2			
PART – A (Normal OPC)						
50 x 50 x 50	1:3		1 day	3 days	7 days	28 days
	NMC	0	–	15.87	26.3	44.6
	EPNC	0.5	8.26	12.76	16.2	23.32
		0.75	9.4	13.64	20.44	31.22
		1	10.31	14.58	22.5	35.94
		1.5	12.71	23.33	33.44	44.33
		2	18.37	27.83	41.44	44.05
		2.5	19.84	32.27	43.8	45.57
PART – B (Alccofine 1108)						
50 x 50 x 50	MMC	0	15.45	22.71	41.6	52.2
	EPMC	0.5	22.35	31	36	39
		0.75	29	36.08	40.04	44.25
		1.00	30.54	39.37	50.22	61.37
		1.5	31.2	39.85	54	66.47
		2 Epoxy	32.78	44.88	58	70.7
		2.5	34.54	46.4	62	77.15

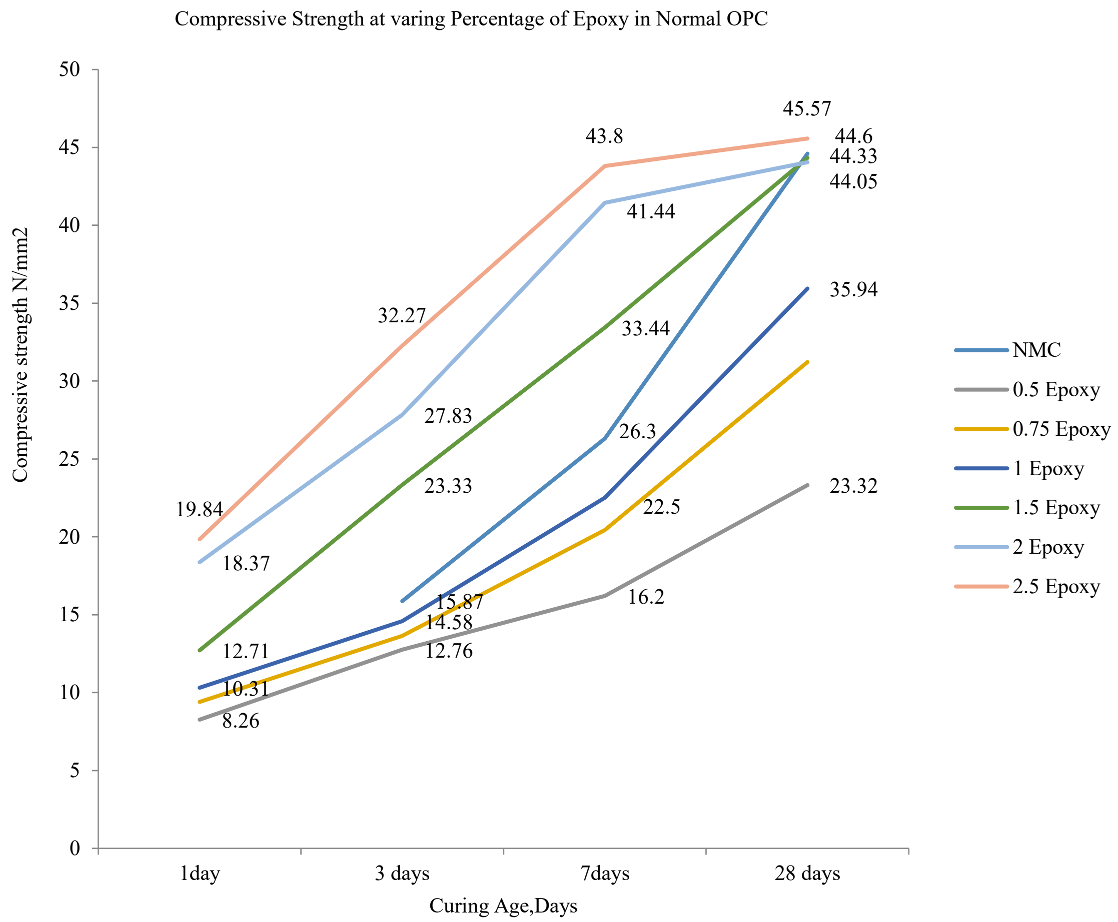

Figure 2. Effect of epoxy on OPC and impact of PSD of cement.

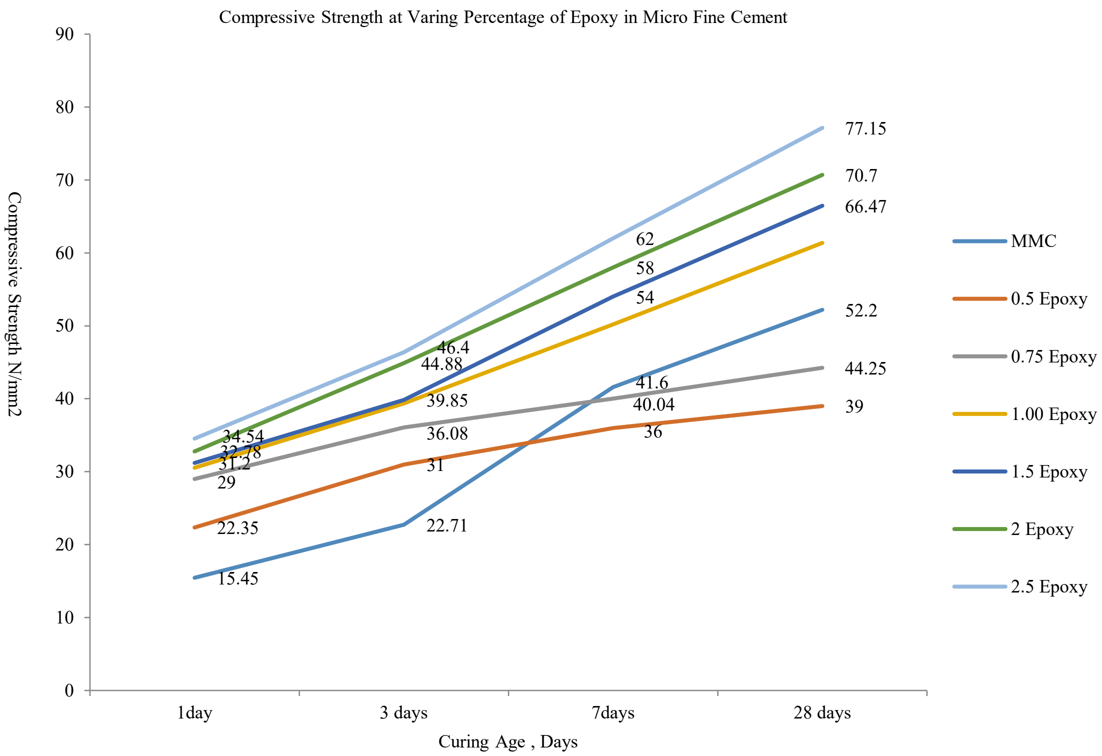

Figure 3. Effect of epoxy on alccofine 1108 and compressive strength variation.

Split Tensile strength and Flexural strength

The specimens were cast using 1% epoxy, micro-fine cement, and standard sand, maintaining a water–cement ratio of 0.46. For the split tensile strength test, cylindrical specimens of 100 mm length and 50 mm diameter were prepared in accordance with standard procedures. For the flexural strength test, beam specimens of size 40 × 40 × 160 mm were cast and tested. The corresponding test results are presented in Table 7.

Table 7. Split tensile strength and flexural strength.

Parameter	**Identification**	**Number of days**			
		1 day	**3 days**	**7 days**	**28 days**
Split tensile strength (N/mm^2)	MMC	2.96	3.95	4.65	5.27
	EPNC	4.24	4.7	5.6	6.4
Flexural tensile strength (N/mm^2)	MCC	3.05	3.7	4.91	5.53
	EPMC	4.33	5.14	6.1	6.6

Effect of Addition of Gypsum on Epoxy-Modified Concrete

Gypsum was incorporated into epoxy-modified micro-concrete to extend both the initial setting time and the final demolding time, while maintaining an epoxy–cement ratio of 2.5%. The dosage of gypsum was varied from 0.5% to 2.0%. The corresponding increase in setting times, in comparison with Normal Micro Concrete (NMC), has been recorded and presented in Tables 8 and 9. The influence of gypsum addition on the setting behaviour is further illustrated in Figure 4. It was observed that the incorporation of gypsum leads to a gradual reduction in compressive strength, although the extent of reduction is not linear. At 0.5% to 1.0% gypsum content, the compressive strength reduction ranges between approximately 10% and 12%, while at 2.0% gypsum content, the reduction increases to about 16%. This indicates a clear dose-dependent relationship, wherein increasing gypsum content progressively affects the strength development of the epoxy-modified micro-concrete system.

Table 8. Effect of addition of gypsum on epoxy modified micro concrete at 2.5% epoxy.

Epoxy–Cement ratio	Gypsum in percentage	Initial moulding time (minutes)	De molding time (minutes)
NMC	0	Not possible to mix and mold	Not possible to mold
2.50%	0.50	20	90
	1.00	40	125
	2.00	70	240

Table 9. Effect of addition of gypsum on epoxy modified micro concrete at 2.5% epoxy.

Epoxy–Cement ratio	Weight (gms)	Percentage of gypsum	Compressive strength (N/mm^2)			
NMC			1 day	1 day	1 day	1 day
2.50%	298	0.00%	34.54	34.54	34.54	34.54
	290	0.5% Gypsum	31.00	31.00	31.00	31.00
	283.33	1.00% Gypsum	30.66	30.66	30.66	30.66
	289.33	2.0% Gypsum	28.93	28.93	28.93	28.93

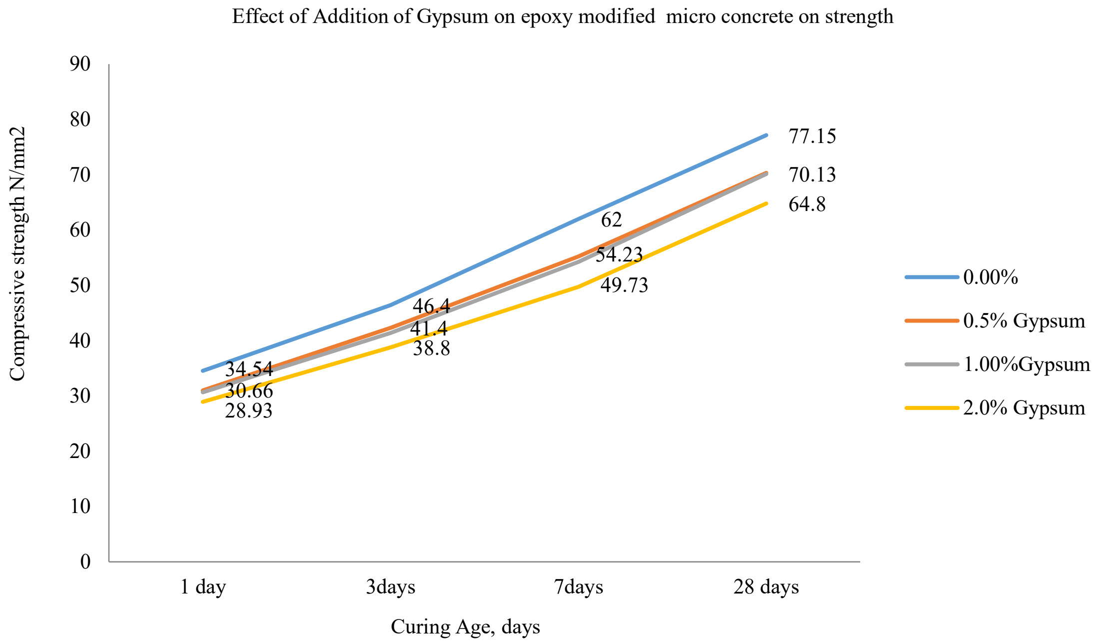

Figure 4. Effect of addition of gypsum on epoxy modified micro concrete at 2.5% epoxy.

The observed correlation between gypsum concentration and the setting kinetics of the composite reveals a significant extension in both initial molding and final demolding times as the quantity of gypsum is increased. Concurrently, a reduction in compressive strength is noted, yet this attenuation remains remarkably consistent at approximately 15% regardless of the specific quantum of gypsum added to the mixture. This unique mechanical behaviour is fundamentally attributed to the inherent properties of epoxy chemistry, suggesting that the epoxy matrix reaches a stabilization point that prevents further linear degradation of strength. Consequently, these findings indicate that the chemical formulation of micro-cement must be precisely aligned with epoxy chemistry, particularly in the context of water–miscible epoxies, to ensure proper interaction between the cementitious hydration process and the resinous cross-linking.

Durability Analysis

In this research, durability assessments were performed in strict accordance with international standards to ensure the methodological reliability and reproducibility of all results. The capillary

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absorption rate was evaluated via the sorptivity test following ASTM C1585, with measurements recorded at intervals of 30, 60, and 120 minutes to characterize the ingress properties of the modified micro-concrete. Resistance to chloride ion penetration was determined through the Rapid Chloride Migration Test (RCMT) as per NT Build 492, utilizing a 60V DC electric potential over a six-hour duration to calculate the non-steady-state chloride migration coefficient. Acid resistance was quantified by submerging specimens in a 1% sulfuric acid solution, following procedures like ASTM C267, with weight loss and residual compressive strength analysed after a 28-day exposure period. These standardized protocols allow the durability performance of the epoxy–Alccofine modified micro-concrete to be accurately benchmarked against existing literature and industry criteria.

Test specimens were prepared using optimized epoxy content, and the subsequent durability findings are summarized in Table 10. The sorptivity analysis revealed that epoxy-modified micro-concrete achieved a 96% reduction in capillary rise absorption compared to the control specimens. During RCMT, the epoxy-modified variants exhibited superior resistance with a lower migration coefficient of 4.55 x 10^{-12} m^2/s, whereas the control MMC recorded 5.55 x 10^{-12} m^2/s. Carbonation testing conducted at sixty days, six months, and one year showed no discernible carbonation effects in either the control or the modified specimens upon application of the indicator solution. In terms of acid resistance, both weight loss and strength retention were monitored after 28 days of immersion, while thermal analysis indicated that weight loss in the epoxy-modified concrete at 60°C, 120°C, and 240°C was consistently 10% lower than that of the standard micro-fine cement concrete. These systematic evaluations provide a comprehensive comparative framework for understanding the enhanced performance of the epoxy-modified composite.

Table 10. Durability analysis of epoxy-modified micro concrete.

Sample ID	**Sorptivity ($mm/min.^{0.5}$)**	**RCMT(m^2/s)**	**Carbonation effect at 365 days**	**Acid resistance test, compressive strength loss in (N/mm^2)**		**Temperature effect. percentage weight loss at 240°**
				Before immersion	***After immersion***	
MMC	1.9	(5.55 x 10^{-12})	Nil	50.54	19.82	4.37
EPMC	0.077	(4.55 x 10^{-12})	Nil	59.54	24.54	3.39
Remarks	96% lower than CC	Good quality	–	Strength loss is 6.64% lower than CC		10% lower as compared to MMC

CONCLUSIONS

Based on the comprehensive experimental investigations and subsequent analytical evaluations, the following conclusions are derived:

- The integration of micro-fine cement into the micro-concrete matrix results in a 1.1% increase in unit weight relative to conventional micro-concrete formulated with Ordinary Portland Cement. Furthermore, epoxy-modified micro-concrete containing micro-fine cement exhibits a 1.7% weight elevation compared to its epoxy-modified counterpart using standard Ordinary Portland Cement.
- Micro-concrete utilizing micro-fine cement demonstrates a 1.4% increase in density over conventional Ordinary Portland Cement micro-concrete. When modified with epoxy, the micro-fine cement variant shows a density increment of 1.77% compared to epoxy-modified micro-concrete based on standard Ordinary Portland Cement.
- Surface morphology analysis reveals that both micro-fine and standard cement-based epoxy-modified micro-concretes maintain a consistently smooth texture at epoxy concentrations up to 1%, signifying optimal phase compatibility and a refined interfacial transition zone.
- Epoxy-modified micro-concrete incorporating micro-fine cement and 1% epoxy content achieves a 20.8% higher compressive strength compared to the control at the seven-day interval. Similarly, a 1% epoxy dosage was identified as the optimal concentration for maximizing the compressive strength of micro-concrete formulated with standard Ordinary Portland Cement.

- The inclusion of epoxy resins enhances the split tensile and flexural strengths of the micro-concrete by 21% and 19%, respectively, relative to the control. However, the introduction of gypsum at higher epoxy concentrations (2.5%) results in a 16% reduction in compressive strength and a significant retardation of the setting kinetics.
- Epoxy-modified micro-concrete demonstrates superior durability metrics, most notably a 96% reduction in sorptivity, indicating a high resistance to capillary moisture ingress. Rapid Chloride Migration Testing further confirms this enhanced barrier performance, with the epoxy-modified specimens showing a 21% decrease in chloride migration coefficients compared to the control.
- Both formulations exhibit negligible carbonation depths, underscoring high resistance to atmospheric CO2 penetration. Additionally, under sulfuric acid immersion, the epoxy-modified micro-concrete demonstrates superior chemical stability, with a 6.64% lower reduction in compressive strength compared to the control.
- Thermal stability assessments indicate that epoxy-modified concrete undergoes a 10% lower percentage weight loss across varying temperature ranges relative to standard micro-fine cement concrete, suggesting improved performance in fluctuating thermal environments.
- This research provides significant insights into the physical, mechanical, and durability attributes of epoxy-modified micro-concrete. The findings validate its potential as a high-performance, durable construction material ideally suited for specialized repair and retrofitting applications, particularly in environments where conventional curing processes are restricted or critical.

Declaration

Authors, hereby declare that the research work presented in this article titled “Experimental Investigations on Influence of Epoxy and Alccofine in Concrete – A Sustainable Approach” is original and has been carried out by me and co-authors. All sources of information used in this research have been acknowledged and referenced appropriately. The data presented and conclusions drawn in this article are based on our own analysis and understanding. We take full responsibility for the authenticity and validity of the content provided herein.

Author Contribution

- *Rajendra Ganapati Hegde:* Conceptualization, Methodology, Investigation, Writing – Original Data Curation, Formal Analysis, Visualization, Writing – Review & Editing
- *K G Guptha:* Supervision, Project Administration, Funding Acquisition, Writing – Review & Editing. Resources, Software, Validation, Writing – Review & Editing.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this article.

Data Availability Statement

All data generated or analyzed during this study are included in this article.

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