Synergizing Design Thinking with Fiber Reinforcement: Innovating Fibre-Reinforced Self-Compacting Concrete Using Carbon and Polypropylene Fibres

Sajeev P S,

Lecturer in Civil Engineering, Government Polytechnic College, Perintalmanna, Kerala.

Email: sajeevpoly@gmail.com

Abstract

This paper introduces the growing importance of Self-Compacting Concrete (SCC) in modern construction due to its self-leveling and formwork-filling capabilities without mechanical vibration. It highlights the incorporation of fibers in SCC to enhance mechanical performance, crack resistance, and durability. The study investigates four SCC mixtures containing polypropylene (PP) fibers at volume fractions of 0.1%, 0.15%, 0.2%, and 0.25%, along with 0.6% volume fraction of carbon fibers. These additions aim to improve the concrete's tensile properties. The research analyzes both fresh and mechanical properties, such as compressive strength, split tensile strength, and flexural strength of SCC, comparing the results. This paper explores the application of design thinking principles in the realm of construction materials, specifically in the development of Fibre Reinforced Self-Compacting Concrete (FRSCC) through the integration of carbon and polypropylene fibers. Design thinking, a human-centered problem-solving approach, is used to refine FRSCC formulation and optimize its performance, aligning functional and structural requirements with user needs. This approach enhances the development of FRSCC, providing a holistic solution to address the multifaceted challenges in the construction industry.

Keywords: Design thinking, Fibre Reinforced Self-Compacting Concrete, carbon fibres, polypropylene fibres and mechanical properties.

1. INTRODUCTION

Self-Compacting Concrete (SCC) is a specialized concrete blend renowned for its unique ability to flow and fill complex formwork without the need for mechanical vibration, making it a key innovation in modern construction. SCC's self-leveling properties significantly enhance construction efficiency and structural integrity. High-Performance Concrete (HPC), on the other hand, is engineered to exhibit superior mechanical and durability characteristics compared to conventional concrete. It achieves this through precise mixture proportions, advanced materials, and meticulous quality control, making it ideal for applications requiring exceptional strength, durability, and resistance to environmental factors. Both SCC and HPC represent critical advancements in the field of concrete technology, contributing to the evolution of contemporary construction practices.

The mechanical properties and fracture behavior of Polyolefin Fiber-Reinforced Self-Compacting Concrete (PF-RSCC). They systematically examine PF-RSCC with different fiber volume fractions, demonstrating enhanced mechanical performance, including increased compressive and flexural strengths. The research also highlights PF-RSCC's improved fracture behavior, with Polyolefin fibers effectively restraining crack propagation and enhancing energy absorption. These findings are pertinent to the construction industry's quest for sustainable, high-performance materials. Published in Construction and Building Materials, a reputable journal, the study provides credible insights, aiding engineers and architects in addressing structural and durability challenges with PF-RSCC's innovative potential. [1]

The properties of Fly Ash Concrete (FAC) enriched with Hydrated Lime and Silica Fume. Their research highlights the substantial improvements these additives bring to FAC, including enhanced workability, reduced water demand, increased early-age strength, and improved long-term durability. This study underscores the potential of FAC as a sustainable construction material and contributes valuable insights for engineers and researchers aiming to reduce the environmental impact of concrete while enhancing its performance. Published in a respected journal, this work serves as a reliable reference for those exploring eco-friendly and high-performance concrete solutions. [2]

Apparent Activation Energy Function for predicting the compressive strength of Fly Ash Concrete, contributing significantly to our understanding of concrete behavior under varying conditions. The research provides a valuable tool for engineers and researchers aiming to predict and optimize concrete performance. [3] The influence of mixing protocols on Self-Compacting Concrete properties, this research offers practical insights into optimizing concrete production techniques. It addresses the critical aspects of workability, consistency, and performance, providing guidance for engineers and concrete producers. [4] The properties of Cement-Fly Ash Grout with various additives, expanding our understanding of material modifications in concrete. It sheds light on the impact of different additives, contributing to the knowledge base on improving concrete properties for specific applications. [5]

Focusing on the mortar phase of Self-Compacting High-Performance Concrete, this research advances our understanding of high-performance concrete design. It explores the intricate properties of the mortar phase, providing insights into optimizing concrete mixes for superior performance and durability. [6] The performance of Polypropylene Fiber-Reinforced Pavement Quality Concrete incorporating Waste Granite Powder. It aligns with sustainability goals by exploring innovative materials and methods for pavement construction. [7] The influence of mineral admixtures on Self-Compacting Concrete under elevated temperatures, addressing concrete performance in challenging conditions. It offers insights into optimizing concrete mixtures for applications exposed to elevated temperatures. [8]

The utilization of Fly Ash with Silica Fume in Portland Cement-Fly Ash-Silica Fume Concrete. It contributes to the understanding of incorporating supplementary materials in concrete mixes to enhance performance and sustainability. [9] The concept of Self-Compacting High-Performance Concrete, emphasizing its remarkable workability and high-performance characteristics. It represents a significant advancement in concrete technology, particularly in the context of ease of placement and high-quality results. [10] Ultra High Performance Concrete reinforced with steel and carbon fibers, this research explores advanced concrete materials and their potential for structural applications demanding exceptional strength and durability. [11]

The mechanical properties of Polypropylene-Fiber-Reinforced High-Performance Concrete using the Response Surface Method for optimization. It offers a systematic approach to improving the performance of high-strength concrete mixes. [12] The effect of temperature, carbon fibers, and silica fume on Lightweight Concrete, contributing to our understanding of concrete performance under varying conditions. It addresses the crucial aspects of lightweight concrete design and durability. [13] The properties of Polypropylene Fiber Reinforced Silica Fume Expansive-Cement Concrete, this research enhances our knowledge of fiber-reinforced concrete materials and their potential for structural and expansion applications. [14] The impact of Silica Fume and High-Volume Class C Fly Ash on Self-Compacting Concrete. It provides valuable insights into the use of supplementary materials for enhanced concrete performance, especially in terms of strength, durability, and resistance to environmental factors. [15]

Self-Compacting Concrete (SCC) is typically installed on building sites as a practical solution to issues related to fling concrete. The tasks of workers, the type and quantity of supplements, or the order of a construction have no bearing on self-compacting concrete. Pumping for longer distances is possible because to its great fluidity and unwillingness to allow segregation. Self-Compacting Concrete is cast in order to prevent supplementary inner or outer vibration. Cement, aggregates, and water are the same components of self-compacting concrete as in conventionally made concrete, but varying proportions of synthetic and mineral chemicals are also added. [16] High-performance concrete (HPC) is an advanced form of concrete that is designed to have better qualities than standard concrete. It is engineered to have increased strength, durability, workability, and other engineering properties that make it appropriate for demanding applications in construction and infrastructure projects. To attain these desired qualities, HPC often entails careful material selection, exact mix proportions, and advanced processing techniques. In this research, normal concrete is upgraded to self-compacting high performance concrete using carbon and polypropylene fibers. [17]

The carbon fiber is a high-performance non-metallic strengthening material. Discussing of carbon fibers, they are made with regulated pyrolysis of appropriate fibers and contain at least 90% carbon. Today, carbon fibers have established itself to serve the needs of the commercial and civilian airplanes, recreation, factories, and automotive markets. In composites with a lightweight matrix, carbon fibers are employed. [18] Polypropylene fiber is frequently used in cement and concrete to increase the ductility and anti-cracking performance of the matrix concrete because to its low modulus of elasticity, high strength, outstanding ductility, excellent durability, and inexpensive price. By enhancing the tensile strength of concrete and bridging developing fissures, polypropylene fibers reduce plastic and early drying shrinkage. [19] In order to reduce the matrix's brittleness and the concrete's susceptibility to cracking, polypropylene fiber is added to the mix. To increase the durability of concrete, polypropylene fibers are added. To lessen the expense and environmental impact, high-content fly ash and manufactured sand are employed. The use of synthetic organic fibers, such as polypropylene fiber (PPF), in HPC has advanced significantly in recent years. [20]

2. MATERIALS USED

2.1 Cement

Ordinary Portland Cement (OPC) stands as the construction industry's predominant cement type, celebrated for its universal adaptability and extensive utility. Crafted through the meticulous grinding of clinker, gypsum, and additional mineral components, OPC emerges as the paramount binding agent in the construction realm. Its defining characteristics encompass exceptional compressive potency, resilience, and precise setting attributes, rendering it a fitting choice for a diverse spectrum of construction undertakings. These qualities have solidified OPC's stature as a fundamental component, upholding its pivotal role in modern construction practices.

2.2 Fine aggregate

The assessment of the properties of the supplied M-Sand yields essential insights into its suitability for construction applications. With a fineness modulus of 2.7, the M-Sand exhibits a diverse particle size distribution, potentially influencing the workability and strength of concrete or mortar in which it is incorporated. Specific gravity of 2.64 indicates that the M-Sand is denser than water. This characteristic is pivotal in comprehending its behavior when combined with other construction materials, impacting the overall density of concrete mixes. M-Sand's remarkably low water absorption rate of 0.8% underscores its limited porosity, rendering it highly resistant to excessive moisture absorption. This quality augments the durability of concrete structures by mitigating moisture-related challenges. Bulk density of 1850 kg/m³ provides valuable data regarding the M-Sand's compactness and weight. This information proves invaluable for meticulous batching and precise mix design procedures in concrete production.

2.3 Coarse aggregate

The comprehensive assessment of the provided coarse aggregate's properties is essential for its effective utilization across a spectrum of construction applications. With a fineness modulus of 6.04, the coarse aggregate reveals a particle distribution that encompasses both fine and coarse components, exerting significant influence over the workability and mechanical attributes of concrete mixes incorporating this aggregate. The specific gravity of 2.74 highlights the coarse aggregate's denseness relative to water, thereby exerting a substantial impact on the overall density and properties of concrete when it assumes the role of a constituent in the mix. The meager water absorption rate of 0.5% underscores the coarse aggregate's inherent low porosity, a highly advantageous trait in concrete production. This characteristic bestows augmented durability by curtailing moisture-related complications. The bulk density, quantified at 1602 kg/m³, furnishes vital insights into the coarse aggregate's compactness and mass. This critical data is indispensable for meticulous batching and precision-laden mix design processes in the realm of concrete production, culminating in outcomes that are both exact and consistent.

2.4 Super Plasticizer

The utilization of high-range water-reducing admixtures, commonly referred to as superplasticizers, holds paramount importance in the realm of concrete technology. These additives play a pivotal role in elevating the flow and workability of concrete mixes while concurrently maintaining lower water-cement ratios. This substantial enhancement in workability facilitates the judicious reduction of water content without any adverse impact on the eventual compressive strength of the resultant concrete structure.In the ongoing research, UNF-5, distinguished as a superplasticizer of repute, has been harnessed to realize these coveted outcomes. UNF-5 falls within the category of high-range water reducers and possesses the distinct classification of sulphonatednapthalene formaldehyde, meticulously adhering to the stringent standards stipulated in ASTM C 494, type F. This superplasticizer assumes a pivotal role as a fundamental constituent in the meticulous optimization of the concrete mixture, assuring that it retains an elevated level of workability, enabling seamless placement, and culminating in the creation of a concrete structure that not only exhibits remarkable strength but also unrivaled durability.

2.5 Viscosity modifying agent

These groundbreaking admixtures are strategically employed to enhance the viscosity of water, thereby effectively addressing concerns such as bleeding and segregation that often arise in fresh concrete. The specific Viscosity Modifying Admixture (VMA) utilized in this research is identified as Glenium Stream-2. This particular VMA assumes a central role in attaining the targeted rheological characteristics of the concrete mixture, facilitating an ideal level of cohesiveness and uniformity. Moreover, it adeptly mitigates the inherent challenges linked to bleed water and the segregation of aggregates during the critical phase of fresh concrete placement.

3. MIX DESIGN

The proportioning of materials for concrete has been done as per the mix design. It is done to obtain concrete with desired performance characteristics. Thus, the mix design for M30 grade of concrete was done in accordance with IS 10262-2019. The mix ratio was 1:2.2:1.5. Table 1 and 2 shows the quantities of materials for convention concrete and design mix.

Table 1. Mix design for M_{30} grade Concrete

Cement	450 Kg/m^3
Fine Aggregate	987.5 Kg/m^3
Coarse aggregate	695 Kg/m^3
Chemical admixtures	2.7 Kg/m^3
Water Cement ratio	0.45

Table 2. SCC trial mixes with Carbon fiber and Polypropylene Fiber

Mixes	Cement Kg/m^3	Flyash Kg/m^3	FA Kg/m^3	CA Kg/m^3	S.P Kg/m^3	P.P Fiber Kg/m^3	Carbon Fiber Kg/m^3
Mix -1	293	158	987.5	695	2.7	0	0
Mix -2	293	158	987.5	695	2.7	0.5	2.7
Mix -3	293	158	987.5	695	2.7	0.7	2.7
Mix -4	293	158	987.5	695	2.7	0.9	2.7
Mix -5	293	158	987.5	695	2.7	1.1	2.7

4. EXPERIMENTAL INVESTIGATION

4.1 Flow-ability test

A range of critical measurements, including Slump Flow (mm), T50 Slump Flow (mm), J-Ring (mm), L-Box (mm), U-Box (mm), and V-Funnel (Sec), assumes significance in the assessment of freshly mixed concrete. The Slump Flow measurement gauges the concrete's capacity to gracefully flow and disperse under its self-weight, delivering crucial insights into its overall consistency and workability. Meanwhile, T50 Slump Flow records the time taken for the concrete to attain its midway flow, shedding light on its deformation rate. The J-Ring, L-Box, and U-Box tests simulate real-world construction conditions, enabling the evaluation of concrete's ability to pass through obstacles and maintain stability. On the other hand, the V-Funnel test, through the measurement of concrete's flow time via a standardized funnel, acts as a reliable indicator of its viscosity and workability. Collectively, these tests play an indispensable role in ensuring that concrete meets predetermined performance criteria and adheres to industry standards, ultimately underpinning the quality, longevity, and structural integrity of construction projects.

4.2 Mechanical properties

Compressive Strength (MPa), Split Tensile Strength (MPa), and Flexural Strength (MPa) represent fundamental mechanical properties that serve as key indicators of concrete's structural performance and durability. Compressive Strength assesses the concrete's capacity to resist axial loads and pressure, providing critical insights into its load-bearing capability and overall robustness. Split Tensile Strength, on the other hand, scrutinizes the material's resistance to forces applied perpendicular to its surface, offering invaluable data on its ability to withstand tensile stresses and combat cracking tendencies. In the realm of bending forces encountered by concrete elements like beams and slabs, Flexural Strength assumes a pivotal role. It evaluates the concrete's aptitude to endure flexural loads and is indispensable in ensuring structural stability, safety, and longevity in construction applications. These three strength parameters collectively constitute a comprehensive framework for evaluating concrete's suitability for specific construction scenarios, guaranteeing that it possesses the requisite strength and durability to withstand anticipated stresses and loads, thereby upholding structural integrity and safety standards.

4.3 Durability properties

The Rapid Chloride Permeability Test (RCPT) and the Water Absorption Test are two crucial examinations employed to evaluate the durability and resilience of concrete in the face of chloride ion intrusion and moisture infiltration. The RCPT provides a quantifiable measure of a concrete sample's susceptibility to chloride ion penetration, a significant concern in aggressive environments like those subjected to marine or deicing salt exposure. This examination aids in the assessment of concrete's capacity to withstand the corrosive impact of chloride ions. Conversely, the Water Absorption Test assesses concrete's porosity and moisture absorption characteristics, furnishing valuable insights into its ability to resist moisture-related problems such as cracking, spalling, and diminished durability. Both tests serve as indispensable instruments for safeguarding the long-term performance and endurance of concrete structures. They empower decision-makers in the construction and maintenance realms to take informed actions that mitigate potential deterioration and elevate the longevity of concrete elements.

4.4 Nondestructive testing

The Rebound Hammer Test represent indispensable non-destructive examination methods employed extensively in the evaluation of concrete's structural soundness and quality. In the Rebound Hammer Test, the concrete surface is struck with a rebound hammer, and the rebound velocity of the hammer is measured, providing a reliable indication of the concrete's compressive strength. This test serves as a valuable tool for assessing the uniformity of concrete within a structure and pinpointing areas of potential concern, such as areas with compromised strength.

5. RESULTS AND DISCUSSION

5.1 Flow-ability test

The presented data assesses the workability and flow characteristics of five concrete mixes through Slump Flow, T50 Slump Flow, J-Ring, L-Box, U-Box, and V-Funnel tests. The trend reveals a consistent reduction in Slump Flow and T50 Slump Flow values from Mix 1 to Mix 5, indicating decreased flowability and slower deformation rates as the mix number increases. The J-Ring test results also demonstrate increased resistance to passing through obstacles with higher mix numbers. Both L-Box and U-Box tests exhibit decreasing values, indicating reduced flowability and deformability. In the V-Funnel test, Mix 5 displays the shortest flow time, suggesting higher viscosity. These findings inform mix selection for specific project requirements. Table 3 shows the results for flow-ability test.

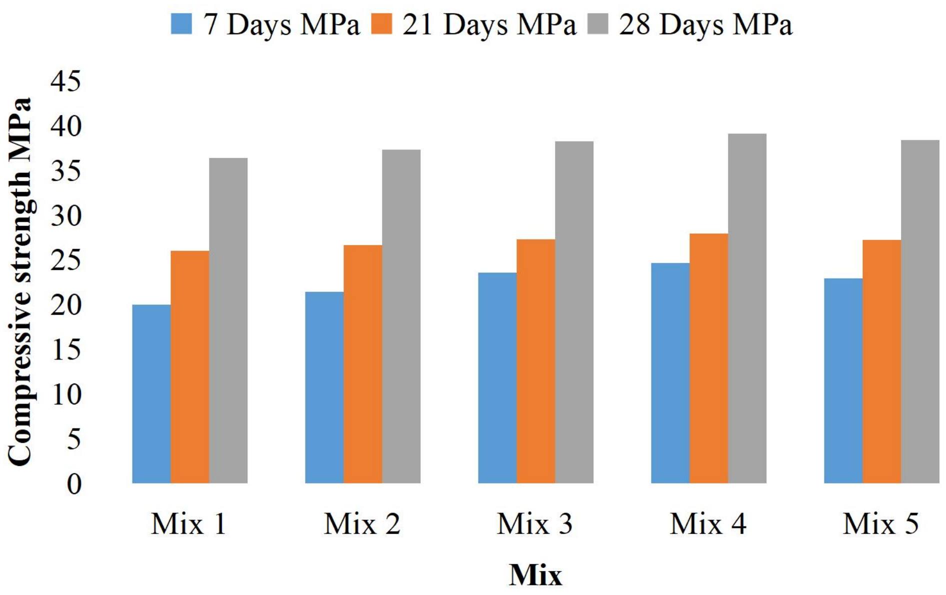
Table 3. Flow-ability test results

Mixes	Slump Flow (mm)	T_{50} Slump Flow(mm)	J- Ring (mm)	L- Box (mm)	U- Box (mm)	V- Funnel (Sec)
Mix 1	780	3	625	0.980	18	8.3
Mix 2	769	4.5	605	0.975	14	7.4
Mix 3	740	5	590	0.969	11	6.8
Mix 4	710	5.4	575	0.959	9	6.4
Mix 5	680	6	550	0.950	6	6

5.2 Mechanical properties

5.2.1 Compressive strength test

The provided data outlines the compressive strength of five concrete mixes at different curing intervals: 7 days, 21 days, and 28 days. A clear pattern emerges, revealing that as the curing duration progresses, all mixes experience an expected increase in compressive strength. Mix 4 consistently exhibits the highest strength values across all three curing periods, followed closely by Mix 3. Notably, Mix 2 demonstrates slightly higher strengths at 7 days compared to Mix 1, indicating variations in early hydration behavior. Overall, all mixes achieve robust compressive strengths at 28 days, with Mix 4 surpassing 39 N/mm^2, signifying their suitability for diverse structural applications. Figure 1 shows the compressive strength test results.



5.2.2 Tensile strength test

The analysis of tensile strength development in five concrete mixes at varying curing intervals of 7 days, 21 days, and 28 days reveals significant insights into their structural suitability. Tensile strength, a critical property in assessing concrete's resistance to cracking and its performance in structural applications, displayed a consistent upward trend with prolonged curing. Mix 4 consistently exhibited the highest tensile strength values, closely trailed by Mix 5, both showcasing superior tensile properties across all durations. These findings highlight the importance of curing duration in enhancing concrete's resistance to tensile stresses and cracking, making Mixes 4 and 5 favorable choices for applications requiring robust structural integrity. Figure 2 shows the tensile strength test results.

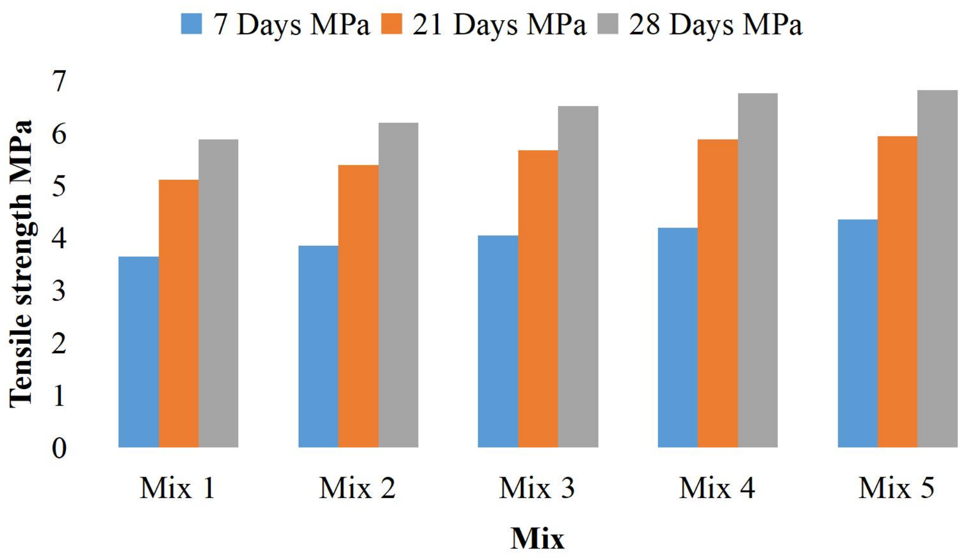


Figure 2. Tensile strength test results

5.2.3 Flexural strength test

The flexural strength test results for five concrete mixes at different curing intervals (7 days, 21 days, and 28 days) reveal critical insights into their suitability for structural applications. Flexural strength, indicative of a material's ability to withstand bending forces, consistently increases with extended curing periods due to ongoing hydration and structural development. Among the mixes, Mix 5 consistently demonstrates the highest flexural strength, closely followed by Mix 4, making them prime choices for structural elements like beams and slabs where resistance to bending and cracking is paramount. These findings aid in informed decision-making for selecting the most suitable concrete mixes for specific construction projects.Figure 3 shows the results for flexural strength test.

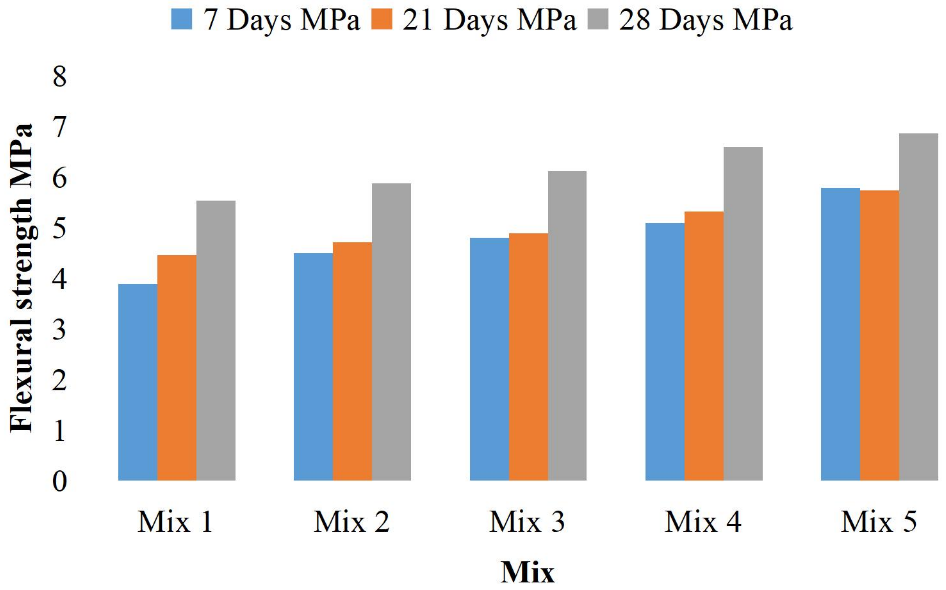


Figure 3. Flexural strength test results

5.3 Durability test

5.3.1 Rapid Chloride Permeability test

The Rapid Chloride Permeability Test (RCPT) results for the concrete mixes classify Mixes 2, 3, 4, and 5 as "Very low" in terms of permeability to chloride ions, indicating exceptional resistance to chloride penetration. This is crucial for structures exposed to chloride-rich environments, such as marine or deicing salt exposure. These mixes exhibit superior durability, safeguarding against the corrosive effects of chloride ions, which can lead to structural deterioration. These findings highlight the suitability of Mixes 2, 3, 4, and 5 for construction projects in challenging conditions, ensuring the long-term durability and integrity of structures in chloride-exposed environments.Figure 4shows the results of RCPT.

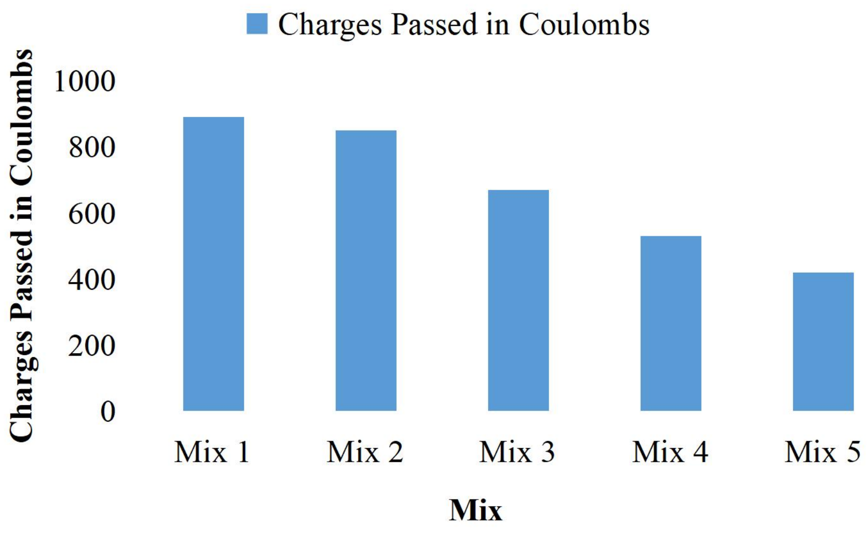


Figure 4. RCPT test results

5.3.2 Water absorption test

The water absorption test results for Mixes 2, 3, 4, and 5 reveal variations in their performance regarding moisture resistance. Mix 2 recorded the highest water absorption at 3.6%, suggesting it has a greater propensity to absorb water, possibly due to its composition or proportions. Mix 3 exhibited a slightly lower absorption rate of 2.95%, indicating improved resistance to moisture compared to Mix 2. Mix 4 displayed further progress, with a 2.53% absorption rate, implying it possesses enhanced water resistance properties, making it suitable for applications in moist environments. Mix 5 demonstrated the lowest absorption at 2.35%, making it a strong choice for scenarios demanding minimal water infiltration. Ultimately, these results underscore the significance of mix composition in determining concrete's resistance to water, guiding its selection for specific construction applications and enhancing structural durability. Figure 5 shows the water absorption test results.

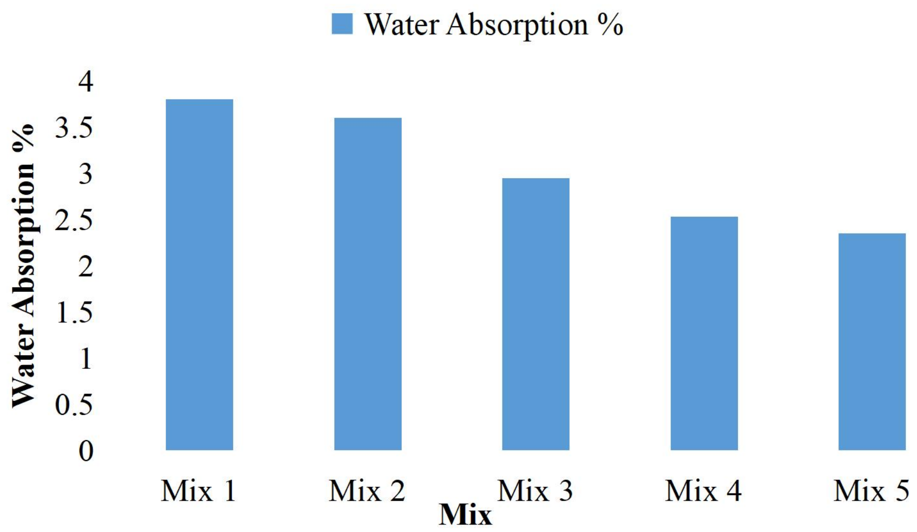


Figure 5. Water absorption test results

5.4 NDT TEST

5.4.1 Rebound Hammer test

The results of the rebound number tests for concrete specimens (Mixes 1-5) provide insights into mix quality. Mix 1 consistently displayed good quality, with stable vertical and horizontal rebound numbers at 36.4. Mix 2, though still "good," had slightly lower mean rebound numbers, particularly horizontally. Mix 3 also showed good quality with slightly higher mean rebound numbers. Mix 4 demonstrated the best quality, boasting the highest mean rebound numbers, signifying structural integrity. Mix 5, like Mix 1, showed good quality. Overall, all mixes performed well, and these findings aid in selecting suitable concrete mixes for construction, ensuring structural durability. Table 9 shows the results of rebound hammer test.

Table 9. Rebound hammer test results

SpecimenID	Vertical(Downward)			Horizontal		
	Mean Rebound	Standard Deviation		Mean Rebound	Standard Deviation	Quality ofConcret

	Number		Quality ofConcrete	Number		e
	Q	s		Q	s	
Mix 1	36.4	3.4	Good	36.4	2.8	Good
Mix 2	37	3.5	Good	29.9	2.6	Fair
Mix 3	38	3.0	Good	31.8	5.7	Good
Mix 4	39.2	3.6	Good	35.3	4.5	Good
Mix 5	38.5	4.3	Good	38	3.2	Good

6. Conclusion

- The highest compressive strength was achieved by Mix-3 with addition of 0.2% of polypropylene and 0.6% carbon fibers, which was found about 39.41 N/mm^2 compared with other mix.
- The highest splitting tensile strength was achieved by Mix-4 with addition of 0.25% of polypropylene and 0.6% carbon fibers, which was found about 6.82 N/mm^2 compared with other mix.
- The highest Flexural strength was achieved by Mix-4 with addition of 0.25% of polypropylene and 0.6% carbon fibers, which was found about 6.87 N/mm^2 compared with other mix.
- Based on the experimental results, the optimum mix is taken as mix – 4.
- The inclusion of fibre in concrete decreases the permeability with increase in addition of fibres. Thus, the FRSCC is capable of resisting chloride ion penetration.
- Water absorption of concrete decrease with increase in percentage of fibre.

REFERENCE

1. A. Naveen Arasu, S. Vivek, J. Robinson & T. ThilakRanjith, ‘Experimental analysis of waste foundry sand in partial replacement of fine aggregate in concrete’, International journal of Chemtech Research, vol. 10, pp. 605-622.

2. Akshana, V., A. Naveen Arasu, and P. Karthigaiselvi. "Experimental study on concrete by partial replacement cement with silica fume." Journal of Critical Reviews 7.17 (2020): 3801-3805.

3. Alberti, M. G., A. Enfedaque, and J. C. Gálvez. 2014. “On the Mechanical Properties and Fracture Behavior of Polyolefin Fiber-Reinforced Self-Compacting Concrete.” *Construction and Building Materials* 55 (March): 274–88. https://doi.org/10.1016/j.conbuildmat.2014.01.024.

4. Arasu, N., Rafsal, M. M., & Kumar, O. S. (2018). Experimental investigation of high performance concrete by partial replacement of fine aggregate by construction demolition waste. International Journal of Scientific & Engineering Research, 9(3).

5. Barbhuiya, S. A., J. K. Gbagbo, M. I. Russell, and P. A. M. Basheer. 2009. “Properties of Fly Ash Concrete Modified with Hydrated Lime and Silica Fume.” *Construction and Building Materials* 23 (10): 3233–39. https://doi.org/10.1016/j.conbuildmat.2009.06.001.

6. Han, Sang-Hun, Jin-Keun Kim, and Yon-Dong Park. 2003. “Prediction of Compressive Strength of Fly Ash Concrete by New Apparent Activation Energy Function.” *Cement and Concrete Research* 33 (7): 965–71. https://doi.org/10.1016/S0008-8846(03)00007-3.

7. Hemalatha, T., K. R. Ram Sundar, A. Ramachandra Murthy, and Nagesh R. Iyer. 2015. “Influence of Mixing Protocol on Fresh and Hardened Properties of Self-Compacting Concrete.” *Construction and Building Materials* 98 (November): 119–27. https://doi.org/10.1016/j.conbuildmat.2015.08.072.

8. Huang, Wei-Hsing. 1997. “Properties of Cement-Fly Ash Grout Admixed with Bentonite, Silica Fume, or Organic Fiber.” *Cement and Concrete Research* 27 (3): 395–406. https://doi.org/10.1016/S0008-8846(97)00032-X.

9. Matos, Ana Mafalda, Lino Maia, Sandra Nunes, and Paula Milheiro-Oliveira. 2018. "Design of Self-Compacting High-Performance Concrete: Study of Mortar Phase." *Construction and Building Materials* 167 (April): 617–30. https://doi.org/10.1016/j.conbuildmat.2018.02.053.

10. Murthi, Palanisamy, VelpulaLavanya, AlirezaBahrami, and KolandasamyPoongodi. 2023. "Performance Evaluation of Polypropylene Fiber-Reinforced Pavement Quality Concrete Made with Waste Granite Powder." *Buildings* 13 (5): 1294. https://doi.org/10.3390/buildings13051294.

11. N, Anand, Antony Godwin I, and Prince Arulraj G. 2016. "Influence of Mineral Admixtures on Mechanical Properties of Self-compacting Concrete under Elevated Temperature." *Fire and Materials* 7 (40): 940–58. https://doi.org/10.1002/fam.2353.

12. Naveen Arasu A, Natarajan M, Balasundaram N &Parathasaarathi R 2023, 'Optimization of high performance concrete composites b using nano materials', Research on Engineering Structures and Materials, Issue 3, Vol. 9, pp 843-859.

13. Naveen Arasu N, Natarajan M, Balasundaram N, Parathasaarathi R 2023, 'Utilizing recycled nanomaterials as a partial replacement for cement to create high performance concrete', Global Nest Journal, vol. 6, no 25, pp. 89-92.

14. Nochaiya, Thanongsak, WatcharapongWongkeo, and ArnonChaipanich. 2010. "Utilization of Fly Ash with Silica Fume and Properties of Portland Cement–Fly Ash–Silica Fume Concrete." *Fuel* 89 (3): 768–74. https://doi.org/10.1016/j.fuel.2009.10.003.

15. R. Prabhu, A. Naveen Arasu, D. Ranjini, (2020), INVESTIGATION ON PARTIAL REPLACEMENT OF CEMENT BY GGBS, JOURNAL OF CRITICAL REVIEWS, 7(17), 3827-3831.

16. Šahmenko, Genadijs, AndrejsKrasnikovs, ArtūrsLukašenoks, and MārisEiduks. 2015. "Ultra High Performance Concrete Reinforced with Short Steel and Carbon Fibers." *ENVIRONMENT. TECHNOLOGIES. RESOURCES. Proceedings of the International Scientific and Practical Conference* 1 (0): 193–99. https://doi.org/10.17770/etr2015vol1.196.

17. Song, Min, Nixia Song, Yunlong Zhang, and Jing Wang. 2022. "Mechanical Properties of Polypropylene-Fiber-Reinforced High-Performance Concrete Based on the Response Surface Method." *Advances in Materials Science and Engineering* 2022 (March): e9802222. https://doi.org/10.1155/2022/9802222.

18. Arasu, A. N., Natarajan, M., Balasundaram, N., &Parthasaarathi, R. (2023). Development of high-performance concrete by using nanomaterial graphene oxide in partial replacement for cement. In AIP Conference Proceedings (Vol. 2861, No. 1). AIP Publishing.

19. A. Naveen Arasu, V.P. Praveen, S. Ramasamy, D. Viveak Harvey, (2020), An Experimental Analysis on Bio Concrete with Bentonite as Partial Replacement for Cement. International Research Journal of Engineering and Technology, 7 (10), 689-695.

20. Yazıcı, Halit. 2008. "The Effect of Silica Fume and High-Volume Class C Fly Ash on Mechanical Properties, Chloride Penetration and Freeze–Thaw Resistance of Self-Compacting Concrete." *Construction and Building Materials* 22 (4): 456–62. https://doi.org/10.1016/j.conbuildmat.2007.01.002.