International Research Journal on Advanced Engineering Hub (IRJAEH)
e ISSN: 2584-2137
Vol. 02 Issue: 03 March 2024
Page No: 622 - 628
https://irjaeh.com
https://doi.org/10.47392/IRJAEH.2024.0090

A Review on the Investigation of Durability Performance of High-Performance Concrete with Cementitious Materials

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Abstract

This in-depth examination investigates the ever-evolving area of High-Performance Concrete (HPC), which has seen growth in the amount of research conducted on it because of its increasing use in the construction industry. This review aims to investigate the longevity of high-performance concrete, that emphasizes Fly Ash, Silica Fume, GGBS, Colloidal Silica and an extensive variety of cementitious components and investigate the ways in which curing conditions, mix ratios, and exposure to the environment influence the overall durability performance of HPC combinations. The environmental and performance implications of using cement in HPC and the potential benefits of substituting cement with cementitious materials like GGBS, Fly Ash and Silica Fume are critically reviewed. Cement production is a substantial contributor to CO2 emissions, and it poses significant environmental challenges with the industry accounting for nearly about 8% of global anthropogenic CO2 emissions. The incorporation of cementitious materials into HPC has been identified as a viable strategy to mitigate these environmental impacts. These materials not only reduce the carbon footprint by decreasing cement consumption but also enhance the concrete's mechanical properties and durability performance. The use of GGBS has been shown to improve the strength and serviceability properties of concrete, contributing to a denser microstructure and increased resistance to chloride penetration. It also improves mechanical and durability properties of HPC including enhanced impermeability and resistance to chloride-ion permeability. The review provides a summary of current research findings and offers incisive suggestions for enhancing the long-term durability of HPC. This is accomplished by carefully examining how cementitious materials impact crucial durability characteristics such as permeability, sulphate attack, chloride penetration and carbonation.

Keywords: *High-Performance Concrete (HPC), Cementitious Materials, Durability, GGBS, Silica Fume.*

1. Introduction

HPC is an advanced and revolutionary substance within the domain of construction engineering. Its purpose is to demonstrate enhanced mechanical and longevity characteristics in comparison to traditional concrete. Considering the increasing emphasis on sustainable and resilient construction

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practices and the changing demands of facilities it is critical to comprehend the long-term durability of HPC. [1]. When assessing concrete materials, durability emerges as a pivotal factor, especially in structures that are subjected to severe environmental conditions, aggressive chemicals, and fluctuating loading conditions by integrating additional cement, specialized chemicals, and rigorous quality control protocols. The aim of this review is to provide an analysis of emergent trends and technologies within the field of HPC for sustainable and durable construction, with a particular focus on recent advancements that contribute to its continuous evolution. Concrete structures will inevitably be subject to durability issues, including freeze-thaw cycles, reinforcing corrosion, alkali-silica reaction, and sulphate assault, all of which are associated with fractures caused by mechanical, thermal, and chemicals [2]. Accelerating the degradation process of concrete structures may result in a reduced service life; however, it can also lead to increased life cycle costs as meticulous monitoring, regular maintenance, and rehabilitation become necessary. For applications involving harsh environments, conventional concrete is unsuitable. In contrast to ready mix concrete. Pozzolanic materials are scarce and cannot substitute for more than 60% of the cement mass in concrete due to their numerous drawbacks, which include decreased workability and increased water demand. It results in optimum strength, efficiency, and production. Considerable research has been devoted to examining the feasibility of substituting Portland cement with SCMs derived from industrial byproducts like Fly Ash, zeolite, ash of rice husk, palm oil clinker, and pyrite cinders, beyond a reduction in strength, these materials may also experience a decline in additional properties. [3]. Given the concerns surrounding the economy, the environment, and the expense of cement, it is possible to replace it with cementitious materials like GGBS, Silica Fume and Fly Ash, which have a 40% lower CO2 emission. In the current context, it is critical to make the concrete industry sustainable to lessen the negative environmental consequences that it has.

Table 1 Comparison Between the Composition of UHPC, HPC and Conventional Concrete Source

Component	UHPC	HPC	Conventional Concrete
Portland cement (kg/m3)	600-1000	400	<400
Coarse aggregate (kg/m3)	-	900	1000
Sand (kg/m3	1000-2000	600	700
Silica fume (kg/m3)	50-300	40	-
Reinforcement/ Fibers (kg/m3)	40-250	Design	Design
Superplasticizer (kg/m3)	10-70	5	-
Water(kg/m3)	110-260	100-150	>200
Aggregate size (mm)	19.0-25.5 & 0.15-0.6	9.5-12.5	19.0-25.5
water-cement ratio (by weight)	0.14-0.27	0.24-o.38	0.40-0.70
water-binder ratio (by weight)	0.27	<0.38	-

The table 1 presents a comparison of the constituents of standard concrete, HPC and UHPC. UHPC distinguishes itself through the incorporation of silica fume (50–300 kg/m3), a higher cement concentration (600–1000 kg/m3), and a significant sand content (1000–2000 kg/m3), all of which contribute to its enhanced strength and durability. It incorporates fibre reinforcement (40-250 kg/m3) and a specific range of superplasticizers (10-70 kg/m3) to enhance workability. UHPC maintains a modest ratio of water to cement (0.14–0.27). and demands exact water management (110-260 kg/m3). Notably, UHPC differs from HPC and traditional concrete in that its aggregate sizes range from 19.0 to 25.5 mm and 9.5 to 12.2 mm. When compared to other materials, UHPC is positioned as an advanced and high-performance material due to these combined qualities [4]. Various experimental work and studies have been carried out to substitute cement with cementitious

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https://doi.org/10.47392/IRJAEH.2024.0090

materials like Silica Fume (SF), Colloidal Silica, Ground Granulated Blast-furnace Slag (GGBS), Fly Ash, and Polypropylene (PP) fibre in different grades of concrete at varying replacement ratios of these materials.

2. Effect of Cementitious Materials On Hpc's Durability Performance

Dhundasiet al [5] examined the durability of ultra-high strength reactive powder concrete (RPC) with compressive strengths of 110, 120, and 130 MPa against aggressive environments. experiments on acid immersion using various doses of sodium sulphate and sulfuric acid, chloride-ion penetration and salt crystallisation tests were carried out. The findings indicate that while greater sulphuric acid concentrations significantly reduce weight and compressive strength. Whereas smaller concentrations have no effect on RPC durability. RPC first resists the crystallisation of salt, but after longer cycles, disruption happens. The study highlights RPC's potential in harsh conditions by confirming its great resistance to chloride ion penetration. A. Elahi et al [6] conducted an experimental study to assess the durability and mechanical parameters of HPC with extra cementitious ingredients in binary and ternary systems. In which water absorption, electrical resistivity, air permeability, and chloride diffusion tests were carried out by researcher. The variety and quantity of additional cementitious materials tested were Fly Ash, GGBS and silica fume. Up till 40% of the Portland cement, 15% of the silica fume, and 70% of the GGBS were substituted with fly ash. The data show that silica fume outperforms other supplemental cementitious components in terms of bulk resistivity and strength growth. The ternary mixes, including GGBS, SF and Fly Ash, performed the best at preventing the diffusion of chloride out of all the mixes. The mixture, which included fly ash, had excellent permeation outcomes. It may be said that every ternary combination produced high-performing concretes with exceptional durability qualities. In an experimental study, S. Niloofar et al [7] examined the durability and frost resistance of regular concrete, no-fibre concrete with nanoparticles, and concrete with polypropylene (PP) fibres. They discovered that nanoparticles outperform PP fibres in terms of concrete frost resistance. The concrete with 5% NS and 0.2% PP fibres had the strongest frost resistance (measured by concrete volume). Durability was increased by 87%. PP fibres improve concrete's frost resistance. However, the improved frost resistance of concrete including nanoparticles exceeds that of concrete containing PP fibres. S. Praveenkumar et al [8] Designed M60 grade concrete using BA (bagasse ash) as cement replacement levels between 0% to 20% on the interval of 5%. Saturated water absorption, porosity, alkalinity measurement and sorptivity tests were performed by author. Results indicate that percentage of saturated water absorption readings of BA decreased reasonably. When BA content increases up to 20%, sorptivity reduces gradually as compared to the control mix. In porosity test, HPC mix without BA was higher than the BA-blended mixes. However, with the help of alkalinity measurement they found that sample of without BA showed higher pH value than the sample of blended BA. Adorjan Borosnyoi et al [9] evaluated durability qualities of HPC with thirteen distinctive HPC combinations. Each combination having varied degrees of Metakaolin and SF substitution for Portland cement, both separately and together. Metakaolin was substituted at ratios of 10%, 17%, 25%, and 33%, and SF was substituted at 3%, 5%, 10%, and 15%. Metakaolin/silica fume (MK/SF) ratios of 7/3, 12/5, 17/8, and 25/8 were used in combination to provide total substitution ratios of 10%, 17%, 25%, and 33%, in that order. Tests like water absorption, watertightness and porosity were performed. During the water absorption test, no improvement in apparent porosity was seen with the combined use. Metakaolin resulted in higher water absorption with higher substitution ratios, whereas SF had lower water absorption due to the higher replacement percentage. When compared to specimens with individual SCMs, those with coupled SCMs had higher water absorption. For watertightness, it was discovered that the best cement replacement

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Page No: 622 - 628
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https://doi.org/10.47392/IRJAEH.2024.0090

percentage for silica fume was 5%, but metakaolin performed poorly within the investigated spectrum. When compared to the reference mix, there was a cumulative 10% reduction in water absorption level at a cement substitution ratio of 33%. An experimental work done by Chougale J. B. et al [10] to examine the effects of M-Sand, MS, and GGBS on the durability characteristics of HPC. In the experiment, he tested multiple replacement combinations, which included partial replacement of OPC with MS, GGBS, and GGBS/MS combinations. In the HPC combinations, OPC was substituted with GGBS at quantities of 40%, 45%, and 50%, as well as with MS at weights of 2.5% and 5%, respectively. Also, combinations like 40% GGBS + 5% MS, 45% GGBS + 2.5% of MS, 45% GGBS + 5% of MS, 40% GGBS + 2.5% of MS, 50% GGBS + 2.5% of MS, and 50% GGBS + 5% of MS were used in replacement of OPC and tested at 28, 56 and 90 days of curing and conclude that, water permeability improved after replacing cement with GGBS but decreased when cement was replaced with MS, and the general water permeability was below 25mm for all combinations. Samples with GGBS substitution exhibited more scattered nanoparticles than the control mix, according to SEM testing. The general outcome of the study suggests that a combination of MS, GGBS, and partial substitution of OPC with GGBS can produce more durable and effective results than the control mix.

3. Effect of Cementitious Materials On Hpc's Mechanical Properties

Experimental work was carried out by Raghavendra et al [11], in which cement was substituted for GGBS in three different cement contents—450 kg/m3, 400 kg/m3, and 350 kg/m3—for a range of water-to-cement ratios—0.45, 0.35, and 0.4, respectively. They recorded the temperature, air content, slump, setting time, and compression strength at ages 7, 28, 56, 90, and 180 days during the experiment. The first slump and the 60-minute slump collapsed for the entire replacement percentage, according to the results. Additionally, the slump worsened after 120 and 180 minutes as the proportion of GGBS grew to 80% replacement. Concrete's air content decreased as the percentage of GGBS increased, while its initial and final setting times increased as well. While compared with the control mix, compression strength at 7 and 28 days was consistently lower for all GGBS substitution ratios, and the decline continued as the GGBS concentration increased. It is intriguing that compressive strength at 56, 90, and 180 days gradually increased to 50% replacement, then decreased to 60% to 80% replacement, but it was still less than the control mix. Furthermore, GGBS replacement of up to 50% of the cement may increase tensile strain, according to the study. A review by D. Suresh et al [12] also noted that replacing up to 50% of the cement with GGBS resulted in decreased strength at 7 and 28 days but increased long-term strength at 56 and 90 days, with maximal compressive strength improvements recorded at this replacement level. Chougale J.B. et al [10] examined effects of M-Sand, MS, and GGBS on the structural characteristics of HPC. In the experiment, he tested multiple replacement combinations, which included partial replacement of cement with MS, GGBS, and GGBS/MS combinations. In the HPC combinations, OPC was substituted with GGBS at quantities of 40%, 45%, and 50%, as well as with MS at weights of 2.5% and 5%, respectively. Also, combinations like 40% GGBS + 5% of MS, 45% GGBS + 2.5% of MS, 45% GGBS + 5% of MS, 40% GGBS + 2.5% of MS, 50% GGBS + 2.5% of MS, and 50% GGBS + 5% of MS were used in place of OPC. Through this investigation, researcher evaluated comparing 56 and 90 days to 28 days, compressive strength normally increases. Although the compressive strength decreased at first when GGBS replaced OPC, the desired strength was attained after 90 days. But after ninety days, compressive strength decreased with increasing MS percent. Meenaloshini E et al [13] Designed M50 grade concrete, by incorporating Polyolefin fibres, SF, and Metakaolin. Polyolefin fibre percentages (0.1%, 0.3%, 0.5%) with 10% SF and 10% Metakaolin were tested. Results reveal optimal performance at

0.3% polyolefin fibre content, enhancing compressive (56.21 N/mm2), split tensile (5.90 N/mm2), and flexural strength (7.35 N/mm2) compared to ordinary concrete. Polyolefin fibres address low tensile strength, and HPC with silica fume/metakaolin substitutes outperforms regular concrete. The study suggests polyolefin fibres, SF, and Metakaolin enhance structural performance, reduce water permeability, and improve ductile behaviour in reinforced concrete beams. In another investigation by Adorján Borosnyói et al [9], the effects of mixing alumino-silicate-based SCMs like metakaolin with silica-based SCMs like silica fume were evaluated regarding the durability and long-term mechanical qualities of high-performance concretes (HPC). Thirteen distinctive HPC combinations were tested, each having varied degrees of metakaolin and silica fume substitution for Portland cement, both separately and together. Metakaolin was substituted at ratios of 10%, 17%, 25%, and 33%, and silica fume was substituted at 3%, 5%, 10%, and 15%. Metakaolin/silica fume (MK/SF) ratios of 7/3, 12/5, 17/8, and 25/8 were used in combination to provide total substitution ratios of 10%, 17%, 25%, and 33%, in that order. According to an evaluation of compressive strength tests, the impact of SCMs on compressive strength differed in terms of both its degree and its rate of development. Metakaolin was mainly used to manage mixtures containing both SCMs. The amount of metakaolin added resulted in a decreasing rise in compressive strength. Utilising metakaolin and silica fume together did not perform better in compressive strength than utilising the SCMs separately. Jisong Zhang et al [14] examined how adding FA and SF might improve the sustainability of UHPC and they found that, the addition of 10% and 20% SF produces mechanical qualities that are either comparable to or better than 30% FA replacement. Microstructure analysis reveals the densest matrix with fewer capillary pores exhibits enhanced compressive and flexural strengths. A predictive model using artificial neural networks (ANNs) accurately forecasts UHPC compressive strength, demonstrating low error rates with relevant input variables. The study suggests extending this approach to predict other UHPC properties, emphasising the potential for broader application and sustainability in high- performance concrete.

4. Evaluation of The Behaviour of Hpc at Varying Temperatures

Albert N. et al [15] performed an experiment to find out how high temperatures (600 °C) affected high-performance concrete's permeability. Three different kinds of concrete mixes were developed for this purpose: (a) high performance concrete with PP fibres; (b) high performance concrete with lightweight particles; and (c) control high-performance concrete. Additionally, included here are the findings on the splitting tensile strength, compressive strength, and thermal gradients in the concrete specimens throughout the heating-cooling cycles. Results shows that, addition of PP Fibre by 2% to HPC didn't have drastic effect in concrete. But when aggregate replaced by lightweight aggregate, compressive strength decreased by 36% and split tensile strength decreased by 38%. Author also observed that, when thermal loading increases, permeability of HPC also increases. In thermal treatment, permeability of fibre reinforced HPC was greater at 200 °C and equal at 600 °C than that of control HPC. Trilok G. et al [1] performed experiment on elevated temperatures effect on compressive strength, static and dynamic modulus of elasticity, mass loss, water, and chloride ion permeability. In which, fine aggregates were replaced by rubber fibres of 2-5 mm and 20 mm in width and length respectively. Those rubber fibres aspect ratio was 4 to 10. At 27 °C that is room temperature, three samples were tested, and other samples were tested at different elevated temperatures like (750 °C, 600 °C, 450 °C, 300 °C and 150 °C) with the exposure time of (30 min, 60 min and 120 min.) by using the instrument electrical furnace for heating process. Table 2 shows how much reduction of compressive strength in percentage observed by researcher. As percentage of rubber fibre increases permeability also increases. While microscopic analysis, they observed that, when temperature increases, gap

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https://doi.org/10.47392/IRJAEH.2024.0090

between cement matrix and rubber fibre also increases. At 300 °C (120 min) cement matrix and rubber fibre separated completely which developed voids in HPC. An experimental study by O. Kessal et al [17] provides a statistical model and experimental analysis of HPC that has been exposed to high temperatures. This study's primary goal is to investigate the impact of concrete age exposed to high temperature cycles (20 °C to 1000 °C) on the mechanical and physical characteristics of HPC. Based on ultrasonic pulse velocity and mass loss, the compression strength, flexural strength, dynamic modulus, and physical properties were assessed. The trials were conducted between the ages of 90 and 210. The findings' examination reveals that rising temperatures weaken the concrete's mechanical qualities, particularly after 90 days.

Table 2 Result of Reduction of Compressive Strength (%)

Temperature And Time	Replacement Percentage Of Rubber Fiber	Result Of Reduction Observed
27 °C (Room Temperature)	5%	22.6%
	25%	53.2%
NORMAL COOLING REGIME		
300 °C (30 min)	5%	7.5%
	25%	7.4%
300 °C (120 min)	5%	18.5%
	25%	23.3%
FAST COOLING REGIME		
300 °C (30 min)	5%	23.5%
	25%	27%
300 °C (120 min)	5%	23.5%
	25%	27%
STATIC MODULUS		
300 °C (120 min)	5%	46.1%
	25%	49.2%
DYNAMIC MODULUS		
300 °C (120 min)	5%	61.3%
	25%	60.5%

Conclusion

Numerous research gaps exist in the area with respect to HPC and UHPC, according to a survey of the literature. First off, even though these concrete varieties endurance has been the subject of several studies, more thorough research is required that takes a larger variety of environmental factors into account. To lessen the environmental effect of concrete manufacturing, Additional investigation is necessary to assess the efficacy and longevity of concrete that incorporates innovative cementitious ingredients, waste by-products, or natural elements. This study of literature reviews the use of cementitious materials like SF, FA, GGBS etc. in HPC by replacing cement in some percentage can improve properties of concrete. Some conclusions of the study are as following:

- Durability and strength of HPC improved by replacing cement with cementitious compounds.
- When GGBS replaced with cement in the amount of 50%, it lowers the strength for early days (7 and 28 days) but at 56 and 90 days of curing strength increases.
- Durability and Strength of HPC increases when SF substituted (up to 10%).

Furthermore, there are few integrated studies that look at how various durability characteristics interact, and new high-performance concrete with cementitious materials like colloidal silica & PP fibre are not given enough attention.

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