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A comparative analysis of high-performance concrete: evaluation of strength and durability parameters with alternate fine aggregates and alccofine through response surface methodology model

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ABSTRACT

The study investigates the integration of alternate fine aggregates like Manufactured sand (MS), Crushed Rock Fines (CRF), Eco Sand (ES) into high-performance concrete M75 grade mixes, along with the inclusion of Alccofine 1203 admixture and glass fibers. It explores various replacement levels of the fine aggregates and evaluates the impact of adding Alccofine 1203 and alternate fine aggregates on the concrete performance. Alccofine 1203, a supplementary cementitious material, replaces a part of the binding component in concrete and enhancing the strength and durability properties and also mitigate the alkali-silica reaction. The incorporation of glass fibers improves concrete's bending and tensile strength. The concrete mixes were carefully designed to meet specific strength and durability requirements. A comprehensive testing regimen assessed both fresh and hardened concrete properties, offering insights into overall quality and performance. This research work found that a high-performance concrete mix with 80% crushed rock fines and 20% eco sand exhibited superior strength and durability. Using crushed rock fines not only increased strength, especially when combined with Alccofine 1203, enhanced the strength and also reduced costs associated with manufactured sand. This combination of alternate fine aggregates in concrete mixes can contribute to sustainable construction practices, cost savings, improved concrete performance and regulatory compliance with environmental standards. Strength properties were validated using the Response Surface Methodology (RSM) Model, which evaluates the relationships between variables and concrete strength characteristics. Comparing measured strengths with the model validated predictions and provided insights into concrete mix performance.

Keywords: High-performance concrete; manufactured sand; crushed rock fines; alccofine; response surface methodology model.

1. INTRODUCTION

In recent decades, there has significant growth in infrastructure development, with concrete playing a pivotal role in this expansion. Concrete typically comprises fundamental ingredients, including fine aggregates, coarse aggregates, cement and water. In the modern era, there is a growing emphasis on constructing sustainable and cost-effective infrastructure that offers high-performance in concrete structures. Under severe environmental conditions, conventional reinforced concrete structures have shown signs of deterioration.

To address these challenges, high-performance concrete (HPC) has emerged as an ideal solution. HPC is characterized by its exceptional strength, high flowability, enhanced thermal resistance, and reduced porosity [1]. High-performance concrete (HPC) is characterized as concrete that attains exceptional performance and consistency while adhering to standard practices for material selection, mixing, pouring, and curing. This often involves using a low water-cement ratio to achieve the desired properties [2]. Due to the substantial infrastructural growth witnessed in recent decades, High-Performance Concretes (HPCs) have emerged as pivotal components in the construction industry. This is attributed to their notable features such as a high modulus of elasticity, robust resistance to chemical attacks, elevated density and superior strength. The unrestricted usage and production of cement have imposed a lot of environmental impacts, depletion of natural resources leads to a threat to our ecosystem paved the way for the consumption of industrial by-products as Supplementary Cementitious Materials (SCMs), and alternate fine aggregates in the development of concrete [3].

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Indeed, the incorporation of supplementary cementitious materials like ground granulated blast furnace slag, silica fume, metakaoline, fly ash, and rice husk ash, all of which are industrial by-products, is a prevalent practice for partially replacing cement in the production of High-Performance Concrete (HPC). This systematic utilization serves the dual purpose of optimizing the economics of HPC while progressively enhancing various physical properties such as setting time, workability, durability, early strength gain and long-term performance. This strategic integration of SCMs in concrete formulation reflects the construction industry's commitment to achieve cost effective solutions and simultaneously advancing the overall performance and sustainability of high-performance concrete [4].

Counto Microfine Products Private Limited, a collaborative effort between Ambuja Cements Limited and Anil Counto Enterprises, has unveiled a pioneering micro-fine Supplementary Cementitious Material (SCM) named Alccofine. According to the availability of calcium silicate content, it has three forms alccofine 1101, alccofine 1203 and alccofine 1206. By comparing them, alccofine 1203 is a processed content from ground granulated blast furnace slag which has higher reactivity, higher glass content and lower calcium silicate content meanwhile used as one of the SCMs to alternate the silica fume used in the development of HPCs [5, 6]. Alccofine 1203 has more number of advantages such as improving the durability by the refined pore structure, improved strength, reducing permeability, improving the pump ability of concrete, maintaining the pH level to resist corrosion, mitigation of alkali-silica reaction and compatibility with admixtures. The experimental study focused on high-grade concrete with partial replacement of cement by Alccofine. The results demonstrated that a 10% replacement of Alccofine led to higher strength, and the formulation of a dense Calcium Silicate Hydrate (CSH) gel was identified [7, 8].

Apart from the SCMs in the development of HPCs, 60–75% of the volume of concrete is filled by coarse and fine aggregates. Due to the development of infrastructures, over-exploitation of natural sand was done and now the short supply of materials and causing an environmental impact. The researchers were finding a solution to avoid depleting the natural resources, various alternate fine aggregates were introduced in the concrete such as manufactured sand, crushed rock fines, eco sand, waste glass powder, ceramic dust, and coal dust [9]. Nowadays, manufactured sand is replacing the natural sand in most of the constructions. In this research work, HPCs were developed by utilizing alternate fine aggregates such as manufactured sand, crushed rock fines and eco sand. Prabu et al. have done the investigation on M20 concrete with partial replacement of Eco Sand and GGBS of 0, 10, 20, 30 and 40% by weight of cement and fine aggregates in concrete respectively. Their results concluded that, optimum percentage of 30% GGBS and 20% eco sand replacement showed better mechanical properties [10]. In M40 grade concrete, 15% of eco sand replacement with fine aggregates showed homogenous mix and maximum strength was achieved [11].

Manufactured sand is created by feeding hard stones of various sizes into primary and secondary crushers, ensuring a well graded composition that adheres to specified proportions. This process maintains low impurity levels and achieves a consistent grading of the sand [9]. The specific gravity of manufactured sand closely aligns with that of natural river sand, and the bulk density of manufactured sand is somewhat higher than that of natural river sand. In terms of sieve analysis, natural river sand is finer than manufactured sand, but both materials fall within the same classification, categorized as Zone II.

Crushed rock fines are created by crushing larger stones in primary and secondary crushers, following a process similar to that used for manufacturing sand. The key difference lies in the final crushing and washing steps applied to the crushed materials. This product corresponds to the stage immediately preceding the production of manufactured sand and is frequently found in the market in the form of dust. Accordance to the previous literatures, crushed rock fines tend to contain a higher proportion of finer particles, which can have an impact on the fresh concrete workability property and strength of concrete. To enhance the effectiveness of the materials, it was advisable to select particles that pass through a 4.75 mm sieve and were retained in the 150 micron range. Additionally, incorporating suitable supplementary cementitious materials into the concrete mix can further contribute to the desired properties and performance of the material [12]. KARTHIK *et al*. [13] conducted the investigation on PPC concrete with partial replacement of river crushed stone, 25% replacement of fine aggregate achieved better strength. Eco sand is composed of very fine particles, derived as a by-product from the cement manufacturing process, specifically through a semi-wet process. It has been introduced as a sustainable alternative in concrete production. This finely powdered crystalline silica serves as a substitute for conventional fine aggregates, replacing them to varying percentages in concrete and mortars.

The introduction of eco sand is a notable step toward improving the efficiency and sustainability of concrete. By incorporating the eco sand as a partial replacement for fine aggregate, the utilization of natural resources is reduced. This not only addresses environmental concerns but also helps in solving the problem of disposing of industrial byproducts. The inclusion of eco sand contributes to enhanced strength properties in concrete and aids in forming a denser transition zone within the concrete structure. This dual benefit of environmental conservation and improved concrete performance makes eco sand a promising material for sustainable construction practices [5].

Glass fibres are commonly integrated into high-performance concrete due to their ability to enhance strength and durability, control cracking, resist impact and corrosion, and improve flexural performance and reduced overall weight. This inclusion of glass fibres results in more durable, resilient and long lasting material that is well-suited for a wide range of demanding applications in construction and infrastructure.

The unique aspect of this study lies in the combination of different types of fine aggregates such as manufactured sand, eco sand and crushed rock fines in concrete. This approach yields several benefits and improves the overall performance of concrete, including enhanced workability, increased strength and durability, optimized particle packing, environmental advantages, cost-effectiveness and the ability to tailor properties to meet specific requirements. The use of various fine aggregates offers versatility, improved performance and potential environmental benefits, making it a valuable strategy in modern construction practices. Furthermore, RSM play a crucial role in advancing concrete technology by providing systematic methods for optimization, prediction and understanding of complex factors influencing concrete properties and performance.

Response Surface Methodology (RSM) is a statistical technique used in experimental design and optimization. RSM involves creating mathematical models that describe how different factors affect concrete properties. RSM helps researchers and engineers systematically explore and optimize complex system, prediction accuracy, insights into relationships, statistical rigor, and visualization of data, all of which contribute to advancing concrete technology and improving concrete properties.

The primary goal of this research was to conduct a comparative analysis of the mechanical and durability properties of HPCs incorporating alternate fine aggregates such as natural sand, manufactured sand, crushed rock fines, and eco sand in various proportions along with SCMs of Alccofine 1203 and glass fibre. This study meticulously evaluated the physical and workability properties of all 14 sets of concrete mixes before the casting of specimens. It focussed in assessing the mechanical and durability properties, aiding on determining the optimum proportion of HPC with alternate fine aggregates. Regression analysis helped identify the relationships between these strength properties.

The expected outcomes of the study include identifying the effective utilization of crushed rock fine sand and eco sand as fine aggregate in the HPC mix replacing manufactured sand. The addition of Alccofine 1203 as a partial replacement for cement aims to enhance workability and strength values, especially considering the higher fines content in crushed rock fines within the HPC mix. The mechanical and durability property test results obtained from the study were used to determine the optimum proportion of ingredients for the HPC mix. The validation of these test results was conducted using the RSM statistical model. RSM allowed for a systematic analysis of the relationships between different variables and the concrete's strength and durability properties, helping to validate and optimize the concrete mix design.

2. MATERIALS AND METHODS

The binding material employed in the formulation of High-Performance Concrete was 53-grade Ordinary Portland Cement adhering to the IS 12269:2013 standard [14]. In conjunction with the binding material, Alccofine 1203 was utilized as a partial replacement material. This Alccofine 1203 was possessed a specific gravity of 2.86, with a fineness of 12000 cm^2/gm, conforming to IS 16715:2018 standard [15, 16]. Alccofine 1203 is an ultrafine material primarily composed of low-calcium silicate, possessing an exceptional chemical composition. Its unique characteristics contribute to the absence of detrimental effects when used as supplementary cementitious materials. This inclusion allows for the development of concrete with desired strength qualities, durability, workability, environmental stability and cost-effectiveness [17]. The mechanical property study focussed on the HPC M75 grade concrete mix with varying levels of partial replacement of Alccofine 1203 and glass fibres. The findings indicated that the optimal combination, with 10% Alccofine 1203 and 0.3% glass fibre replacement, exhibited superior strength compared to other replacement percentages. And also the previous research findings indicated that the optimum proportion of Alccofine 1203 in the mix was 10%, as a partial replacement for cement. Beyond this percentage, there was only minimal change observed in the strength properties of the concrete [18, 19]. The inclusion of alccofine 1203 in concrete has been observed to accelerate the rate of both hydration and pozzolanic reaction when compared to conventional concrete incorporating other supplementary cementitious materials [20, 21]. The chemical characteristic properties of Alccofine 1203 and OPC are presented in Table 1. Figure 1 shows the microscopic images and elemental identification of Alccofine 1203.

Natural sand has become scarce nowadays and also over-exploitation of the natural resources reflects the environmental impact. The researchers identified several alternative aggregates for replacing natural sand,

Table 1: Chemical characteristic properties of alccofine 1203 and OPC.

COMPONENT	LIME	SILICA	IRON OXIDE	ALUMINA	MAGNESIA	SULPHURIC ANHRDRIDE
Alccofine 1203 [22]	28.54	28.64	1.167	36.75	–	0.14
OPC	65.84	20.01	4.61	5.3	0.82	2.5

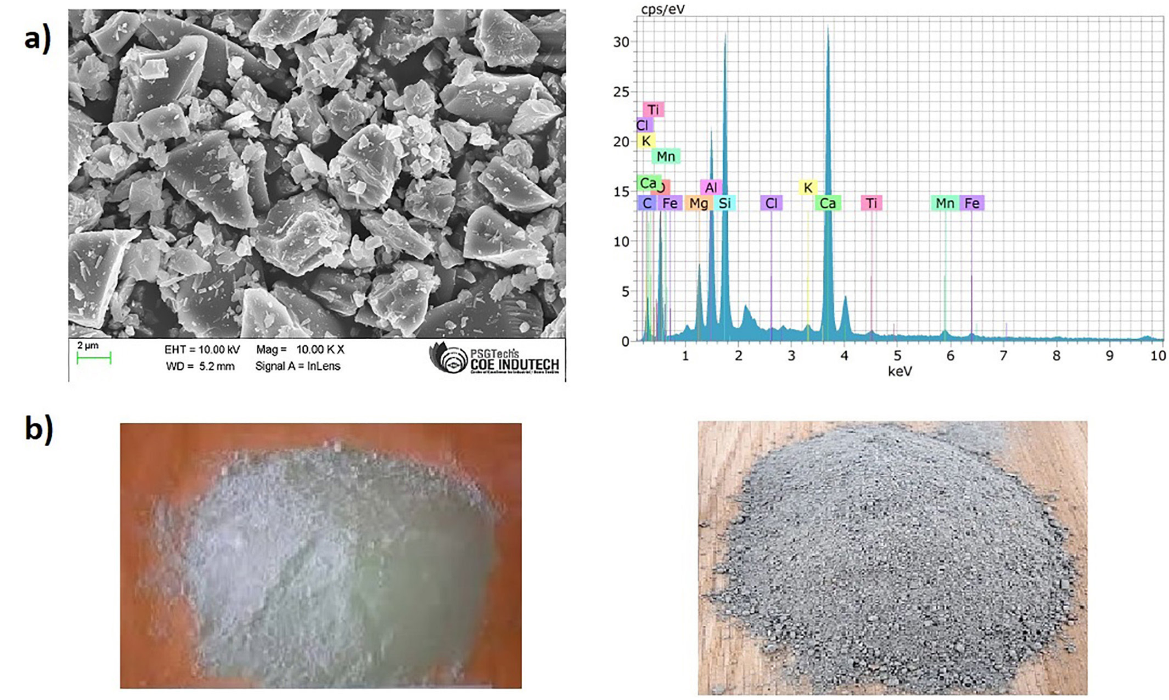

Figure 1: (a) FESEM image and EDAX results of alccofine 1203. (b) Alccofine 1203 and ordinary portland cement.

including manufactured sand, crushed rock fines, eco sand, waste glass powder, ceramic dust and coal dust. In this investigation, the partial replacement of natural sand was carried out using manufactured sand, crushed rock fines and eco sand, adhering to the specifications outlined in IS 383:2016 [23]. The manufactured sand used in the study was procured from a local quarry, and it falls under grading zone II with a fineness modulus of 2.7. These characteristics provide insights into the particle size distribution, density and ability of the sand to absorb water, which are crucial factors in understanding its suitability for use in concrete and construction applications. The crushed rock fines employed as a partial replacement for manufactured sand in the study were sourced from a nearby quarry. These fines have particles that pass through a 4.75 mm sieve and are retained in a 150 micron sieve, placing them within grading zone II with fineness modulus of 2.85. In addition to crushed rock fines, eco sand was partially mixed in the concrete. Eco sand is a by-product from the cement manufacturing industry, generated through a semi-wet process. The characteristics of eco sand, such as its particle size distribution, density and water absorption, would play a role in influencing the properties of the concrete in which it is incorporated. Figure 2 shows the microscopic images and elemental identification of Eco sand. Figure 3 shows the particle size distribution curve of fine aggregates. More amount of silica content was available in the Eco sand as the results obtained form EDAX.

The particle size gradation curve for the fine aggregates used in this study indicates that they fall within Zone II, meeting the upper and lower limits specified for this category. This gradation results were instrumental in preparing high-performance concrete mixes by combining different fine aggregates. This approach ensured that the particle size distribution was optimized for achieving the desired properties and performance in the concrete mixes. The coarse aggregate was of 10 mm size, with a specific gravity of 2.77 and a fineness modulus of 5.96, conforming to IS 383: 2016 standards [23]. For improving the workability of the HPC, Superplasticizer Conplast

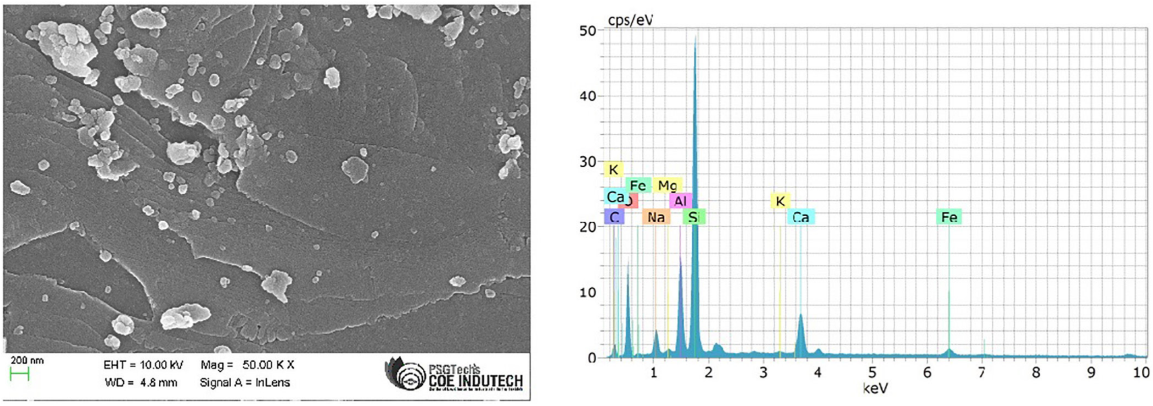

Figure 2: FESEM Image and EDAX results of eco sand.

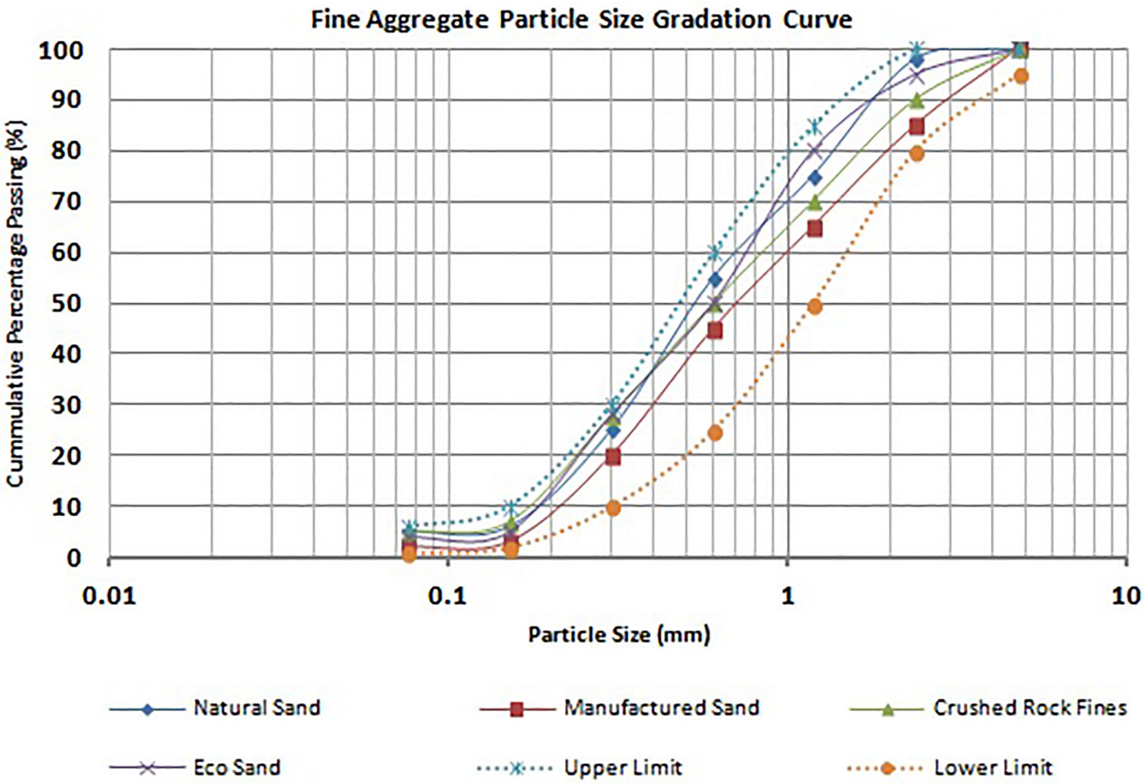

Figure 3: Particle size gradation curve of fine aggregates.

SP430 was mixed conforming to the specification of IS 9103:1999 [24] and cemfill anti-crack glass fibre of filament diameter 14 microns, length 12 mm was used in this investigation along with potable water [12].

3. MIX PROPORTION AND DESIGNATION

The mix design for M75 grade concrete was developed according to the specifications provided in ACI 211.4R-1993 [25]. The concrete mix was prepared through a specific formulation involving several key parameters: Alccofine 1203 was partially replaced in the mix, and the replacement was set at 10% of the weight of the cement. The mix included the addition of glass fibres, constituting 0.3% of the total mix. The water-cement ratio used in the mix was set at 0.26. The formulation of the mix involved a combination of results from previous research works and a trial and error approach [5, 12, 26]. The mix proportions obtained for the concrete mix were specified as 1:1.03:1.973. The details of mix notations and mix proportions are provided in Tables 2 and 3 respectively.

Table 2: Mix proportions.

FINE AGGREGATES	NOTATION	EXPANSION OF NOTATION
Natural Sand (N)	HPCN	HPC with Natural Sand + Alccofine 1203 10% + Glass Fibre 0.3%
Manufactured Sand (M)	HPCM	HPC with MS 100% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCM90E10	HPC with MS 90% + ES 10% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCM80E20	HPC with MS 80% + ES 20% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCM70E30	HPC with MS 70% + ES 30% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCM60E40	HPC with MS 60% + ES 40% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCM50E50	HPC with MS 50% + ES 50% + Alccofine 1203 10% + Glass Fibre 0.3%
Crushed Rock Fines (C)	HPCC	HPC with CRF 100% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCC90E10	HPC with CRF 90% + ES 10% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCC80E20	HPC with CRF 80% + ES 20% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCC70E30	HPC with CRF 70% + ES 30% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCC60E40	HPC with CRF 60% + ES 40% + Alccofine 1203 10% + Glass Fibre 0.3%
	HPCC50E50	HPC with CRF 50% + ES 50% + Alccofine 1203 10% + Glass Fibre 0.3%
Eco Sand (E)	HPCE	HPC with Eco Sand + Alccofine 1203 10% + Glass Fibre 0.3%

Table 3: Mix proportion for one cubic metre of HPC mix.

NOTATION	MIX ID	CEMENT (kg)	ALCCOFINE 1203 (kg)	NATURAL SAND (kg)	MANUFACTURED SAND (kg)	CRUSHED ROCK FINES (kg)	ECO SAND (kg)	COARSE AGGRE-GATE (kg)	GLASS FIBRE (kg)	WATER (LITRE)	CONPLAST SP430 (LITRE)
A	HPCN	472.23	52.47	593	0	0	0	1151	1.75	151	4.7
B	HPCM	472.23	52.47	0	593	0	0	1151	1.75	151	4.7
C	HPCM90E10	472.23	52.47	0	533.7	0	59.3	1151	1.75	151	4.7
D	HPCM80E20	472.23	52.47	0	474.4	0	118.6	1151	1.75	151	4.7
E	HPCM70E30	472.23	52.47	0	415.1	0	177.9	1151	1.75	151	4.7
F	HPCM60E40	472.23	52.47	0	355.8	0	237.2	1151	1.75	151	4.7
G	HPCM50E50	472.23	52.47	0	296.5	0	296.5	1151	1.75	151	4.7
H	HPCC	472.23	52.47	0	0	593	0	1151	1.75	151	4.7
I	HPCC90E10	472.23	52.47	0	0	533.7	59.3	1151	1.75	151	4.7
J	HPCC80E20	472.23	52.47	0	0	474.4	118.6	1151	1.75	151	4.7
K	HPCC70E30	472.23	52.47	0	0	415.1	177.9	1151	1.75	151	4.7
L	HPCC60E40	472.23	52.47	0	0	355.8	237.2	1151	1.75	151	4.7
M	HPCC50E50	472.23	52.47	0	0	296.5	296.5	1151	1.75	151	4.7
N	HPCE	472.23	52.47	0	0	0	593	1151	1.75	151	4.7

A total of 14 sets of mix proportions were prepared for testing mechanical and durability properties at various ages (3, 7, 28, 56 and 90 days). Each set included specimens cast for HPC using natural sand, manufactured sand, crushed rock fines and eco sand. Additionally, there were 5 sets of specimens were cast each for HPC using manufactured sand and partial replacement of eco sand (10, 20, 30, 40 and 50%), and for HPC using crushed rock fines and partial replacement of eco sand (10, 20, 30, 40 and 50%).

Figure 4: Casting and curing process of specimens.

Casting and curing of HPC mixes are indeed critical processes that significantly influence the final properties and performance of the concrete. It is essential to ensure the proper batching of ingredients according to the specified mix proportions, avoiding segregation and bleeding during mixing. Additionally, curing the cast specimens under potable water helps maintain optimal moisture levels and temperature conditions, promoting the development of strength and durability in the concrete. Casting and curing process of concrete specimens are illustrated in Figure 4.

The physical and workability properties were evaluated for all 14 sets of concrete mixes and the specimens were subsequently cast. The study focused on assessing mechanical and durability properties including compressive strength, splitting tensile strength and flexural strength were measured at 3, 7, 28, 56 and 90 days as per Indian Standard IS 516 and the relation between the strength properties was identified with regression analysis. Based on the above mechanical properties of HPCs, the optimum proportion of HPCs with alternate fine aggregates was computed. The durability properties such as water absorption, rapid chloride permeability, void permeability, acid resistance were measured and compared with the optimum proportion mix and the relation between them was identified with RSM regression analysis. The comparative analysis of the mechanical properties with response surface methodology model was done.

4. RESULTS AND DISCUSSION

4.1. Workability

The workability properties of M75 grade concrete were evaluated using various tests, including slump cone, compaction factor, vee bee consistometer and flow table test. The control specimen concrete mix with natural sand showed the slump value as 50 mm, compaction factor as 0.98, flow distance as 147 mm and 5 vee bee seconds compared with the control specimen concrete mix with manufactured sand showed the slump value as 60mm, compaction factor as 0.98, flow distance as 145 mm and 5 vee bee seconds. The substitution of eco sand in both the manufactured sand and crushed rock fines concrete mixes led to a decline in slump value and compaction factor. Additionally, there was a decrease in vee bee seconds, particularly with higher percentages of eco sand. Figure 5 visually presents the outcomes of the workability tests conducted on the M75 grade concrete mix, showcasing the impact of varying degrees of partial replacements with eco sand.

The decline in workability test parameters when adding eco sand to a concrete mix can indeed be attributed to several factors. These include the varying particle sizes affecting packing density, the presence of rougher and angular particles hindering flowability, higher water absorption leading to a drier and stiffer consistency of the concrete mix, and the overall impact on packing and lubrication, which affects the ability of the mix to flow smoothly. The strategies adopted to counter the decline in workability included using Superplasticizer, optimizing mix design, and employing mix optimization techniques. These measures effectively mitigated the decline in workability when adding eco sand and crushed rock fines to concrete mixes, ensuring the concrete maintained its desired performance and properties.

4.2. Compressive strength test

The compressive strength of M75 concrete cubes was assessed using a compression testing machine with a 2000 kN capacity, following the guidelines specified in IS 516 standards [27]. The study involved testing the control concrete mix and variations with eco sand partially substituted by manufactured sand and crushed rock fines. Among the tested mixes, the High-Performance Concrete (HPC) blend comprising 80% crushed rock

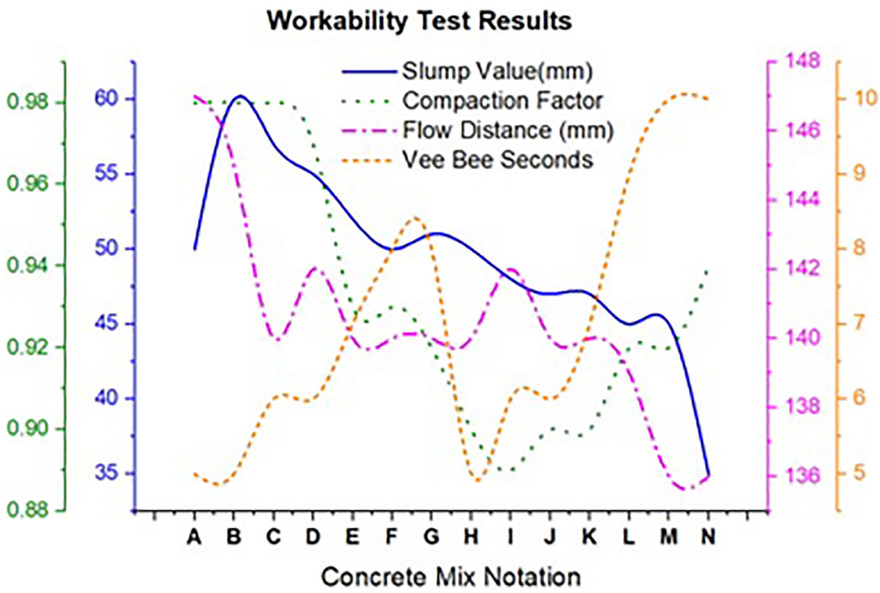

Figure 5: Workability test results of the M75 grade HPC mix.

Figure 6: Mechanical property testing of HPCs specimens.

fines and 20% eco sand (HPCC80E20) demonstrated the higher compressive strength of 84.07 MPa at the 28th day, surpassing both the control specimens and other concrete mixes with partial replacements. However, a reduction in compressive strength was noted when the percentage of eco sand replacement exceeded 20% of the fine aggregate. Specifically, the compressive strengths obtained were 82.35 MPa for the control specimen using natural sand (HPCN), 81.33 MPa for the mix with manufactured sand (HPCM), and 79.47 MPa for the mix incorporating crushed rock fines (HPCC). Notably, the inclusion of crushed rock fines in the concrete blend resulted in higher strength values in the later stages. Figure 6 illustrates the arrangement for conducting mechanical property testing on High-Performance Concrete specimens, and Figure 7a provides a visual comparison of compressive strength results for the HPC mixes at the 14th , 28th, and 90th days.

The addition of eco sand and crushed rock fines as fine aggregates in HPC mix can lead to the higher strength for several reasons such as: (a) both can complement each other in terms of particle size distribution, leads to reducing voids and enhancing the overall density and strength of the concrete, (b) angular and rough texture if crushed rock fines can promote better interlocking between particles, resulting in improved cohesion and shear strength within the concrete matrix, (c) eco sand and crushed rock fines, when properly graded and incorporated in the mix, can reduce the water demand of the concrete, (d) optimized gradation contributes to the higher strength and durability properties in HPC mixes.

4.3. Splitting tensile strength test

The splitting tensile strength of M75 grade concrete cylinders was determined using a compression testing machine with a capacity of 2000 kN, following the protocols outlined in accordance with IS 516 standards [27].

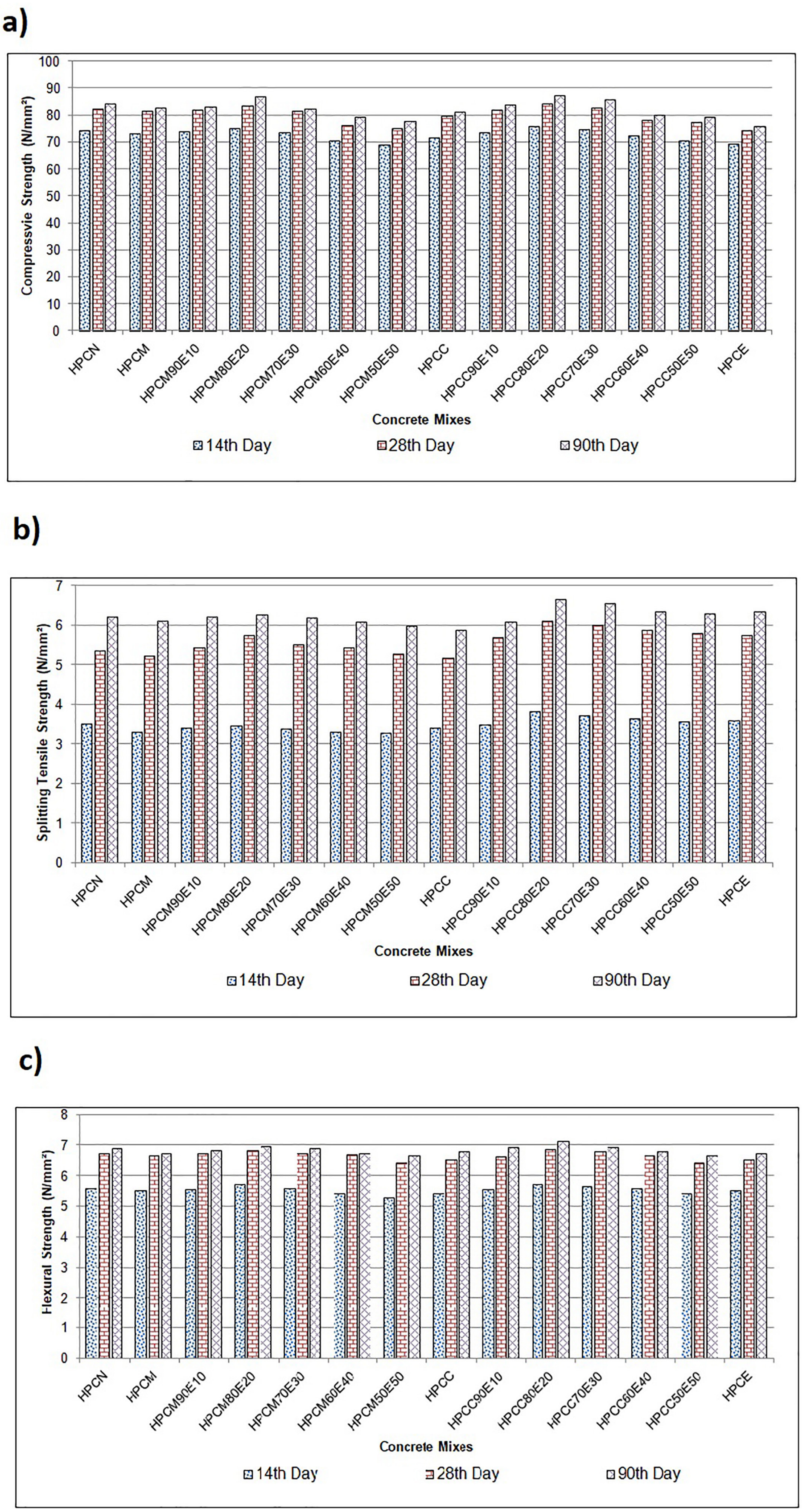

Figure 7: (a) Compressive strength results of the concrete mixes at 14th, 28th and 90th day. (b) Splitting tensile strength results of the concrete mixes at 14th, 28th and 90th day. (c) Flexural strength results of the concrete mixes at 14th, 28th and 90th day.

The study included testing the control concrete mix and variations with partial replacement of eco sand by manufactured sand and crushed rock fines. The High-Performance Concrete (HPC) blend composed of 80% crushed rock fines and 20% eco sand (HPCC80E20) exhibited a higher splitting tensile strength of 6.1 MPa at the 28th day compared to both the control specimens and other concrete mixes with partial replacements. However, an observed trend indicated a reduction in splitting tensile strength as the percentage of eco sand replacement exceeded 20% of the fine aggregate. Specifically, the splitting tensile strengths obtained were 5.35 MPa for the control specimen using natural sand (HPCN), 5.21 MPa for the mix with manufactured sand (HPCM), and 5.17 MPa for the mix incorporating crushed rock fines (HPCC). Notably, the inclusion of crushed rock fines in the concrete mix resulted in higher strength values at later ages. Figure 7b presents a visual comparison of splitting tensile strength results for the High-Performance Concrete mixes at the 14th, 28th and 90th days.

4.4. Flexural strength test

The flexural strength evaluation of M75 grade concrete prism specimens was conducted using a 100 kN capacity flexural testing machine, adhering to IS 516 standards [27]. The study involved testing the control concrete mix and various combinations with partial substitution of eco sand by manufactured sand and crushed rock fines. Among the tested mixes, the High-Performance Concrete (HPC) blend comprising 80% crushed rock fines and 20% eco sand (HPCC80E20) exhibited superior flexural strength, reaching 6.84 MPa at the 28th day. This mix outperformed both the control specimens and other concrete mixes that underwent partial replacements. However, a discernible trend emerged, indicating a decline in flexural strength with eco sand replacement exceeding 20% of the fine aggregate. To elaborate, the flexural strengths recorded were 6.7 MPa for the control specimen using natural sand (HPCN), 6.64 MPa for the mix utilizing manufactured sand (HPCM), and 6.5 MPa for the blend incorporating crushed rock fines (HPCC). Noteworthy is that the incorporation of crushed rock fines in the concrete mix led to higher strength values at later stages. Figure 7c provides a graphical representation of the flexural strength results for the High-Performance Concrete mixes at the 14th, 28th, and 90th days.

4.5. Relation between the strength properties

Figure 8 displays the relationship between the compressive strength and splitting tensile strength of High-Performance Concrete mixes. Regression analysis was conducted to assess the correlation between these strength properties. Table 4 shows the regression analysis results of HPCs mix.

4.6. Modulus of elasticity of HPCs mix

The modulus of elasticity of High-Performance Concrete mixes was determined using a compressometer fixed in the cylinder specimens during testing. Figure 9 illustrates the comparison of modulus of elasticity of all the HPCs mixes. The modulus of elasticity of the HPCs mix 80% of crushed rock fines and 20% of eco sand

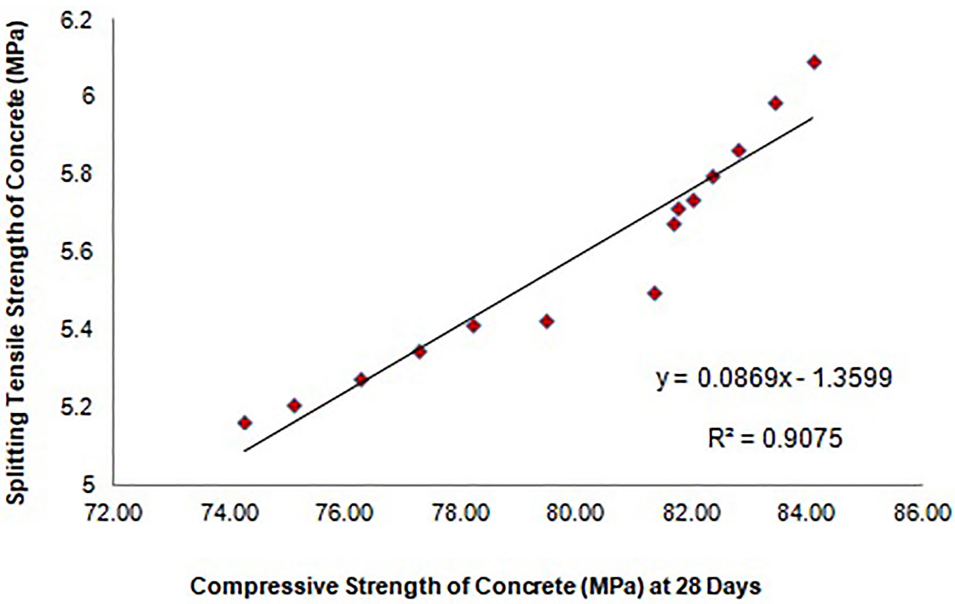

Figure 8: Relation between the compressive strength and splitting tensile strength of HPCs mixes.

Table 4: Regression analysis of HPC mix.

PLOT	B
Equation	Y = a + b*x
Slope	0.08688 ± 0.00801
Intercept	–1.35991 ± 0.64089
Pearson's r	0.95264
Residual Sum of Squares	0.10423
Adj. R-Square	0.89983
R-Square(COD)	0.90753

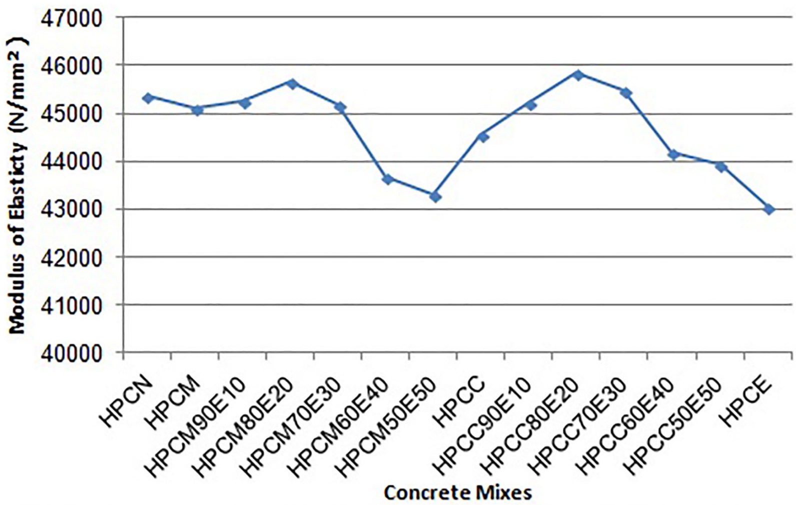

Figure 9: Comparison of the modulus of elasticity of the HPCs mixes.

showed higher value of 45851 MPa when compared with the control specimens and other partial replacement percentages of manufactured sand, crushed rock fines and eco sand. The HPCM80E20 mix showed the nearby value of 45672 MPa.

4.7. Durability properties

Durability of concrete refers to its resistance to deterioration caused by chemical, physical, and biological agents in a specific environment. In this experimental investigation, various durability property tests were conducted, including the Rapid Chloride Penetration Test (RCPT), void permeability test, water absorption test and acid resistance test. Figure 10 shows the durability testing of the HPC mixes.

4.7.1. Rapid Chloride Penetration Test (RCPT)

The RCPT test of High-Performance Concrete mixes was performed using concrete specimens measuring 50 mm in thickness and 100 mm in diameter. These specimens were subjected to a 60V direct current power supply for a duration of 6 hours, adhering to the standards outlines in ASTM C 1202-97. The results of the RCPT for the HPC mixes are depicted in figure 11. The test revealed that the lowest charge of 1372 coulombs was recorded for the HPCC80E20 mix at 28 days. By the age of 90 days, HPCC80E20 mix exhibited a charge of 1009 coulombs. As a consequence of the refinement of the pore structure during the hydration reaction, there is a reduction in the pathways with high conductivity or the paths offering the least resistance for ions.

4.7.2. Water absorption and void permeability test

The water absorption and void permeability test were conducted on 100 mm cube specimens after 28, 56, 90 days of curing, following the ASTM C 642-97 standard procedures. For the water absorption test, the specimens were dried at 105°C and weighed both before and after drying. Saturated water absorption was determined by calculating the percentage variation between the mass of the saturated samples and the mass of the same samples

Figure 10: Durability property testing of HPCs specimens.

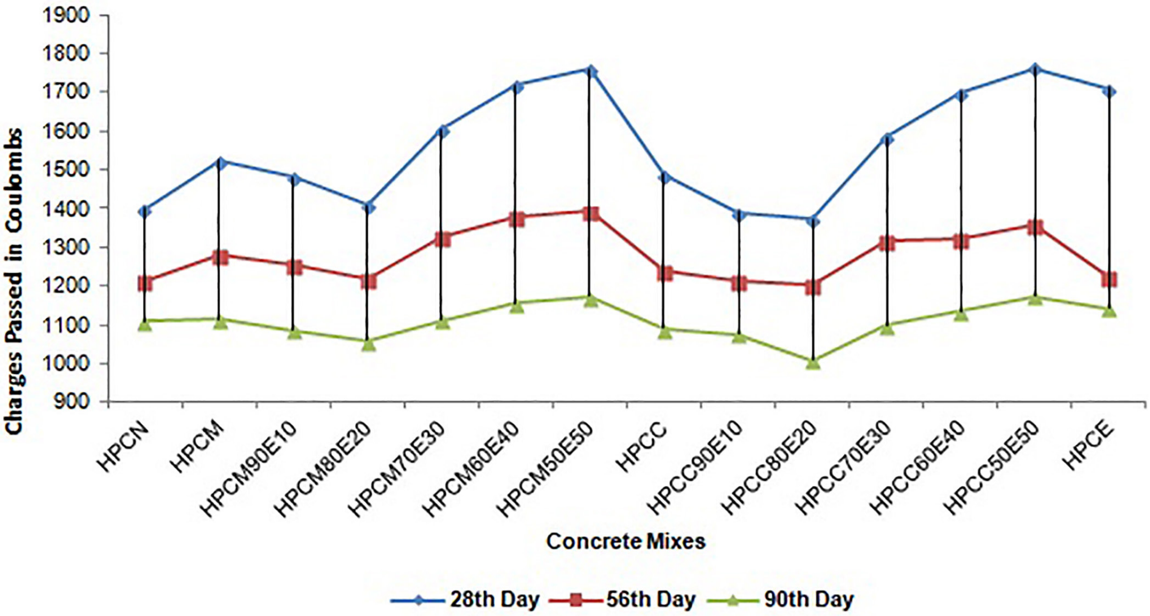

Figure 11: Results of rapid chloride penetration test results for the HPC mixes.

after being dried in an oven at 105°C, expressed as a percentage of the oven-dried mass. In the void permeability test, the difference between the mass of a specimen saturated to its surface dry condition and the mass of the same specimen after being dried in an oven at 105°C, relative to the volume of the samples, was determined. This difference provides insights into the void permeability characteristics of the material.

The water absorption and void permeability tests results are illustrated in figure 12, exhibit interesting findings. The highest water absorption percentage for the high-performance concrete (HPC) mix was 2.94 in the case of HPCM50E50, whereas the lowest value of 1.26 was observed for the HPCC80E20 mix at 28th day. At 90th day, the maximum water absorption of 2.17 was noted for the HPCE mix, while the lowest value of 0.21 was observed for the HPCC80E20 mix.

The lower water absorption levels are attributed to the relatively smaller capillary pore volume resulting from the smaller paste volume. Notably, it was observed that high-performance concrete, incorporating alternate fine aggregates such as crushed rock fines (CRF), displayed reduced water absorption rates. This reduction was due to the smaller capillary pore volume resulting from the smaller paste volume. Similarly, the maximum void permeability value of 6 was recorded for the HPCM50E50 mix, while the lowest value of 3 was observed for the HPCC80E20 mix at 28 days. At 90th day, the maximum value of 5 was obtained for HPCM, while the lowest value of 1.90 was noted for the HPCC80E20 mix.

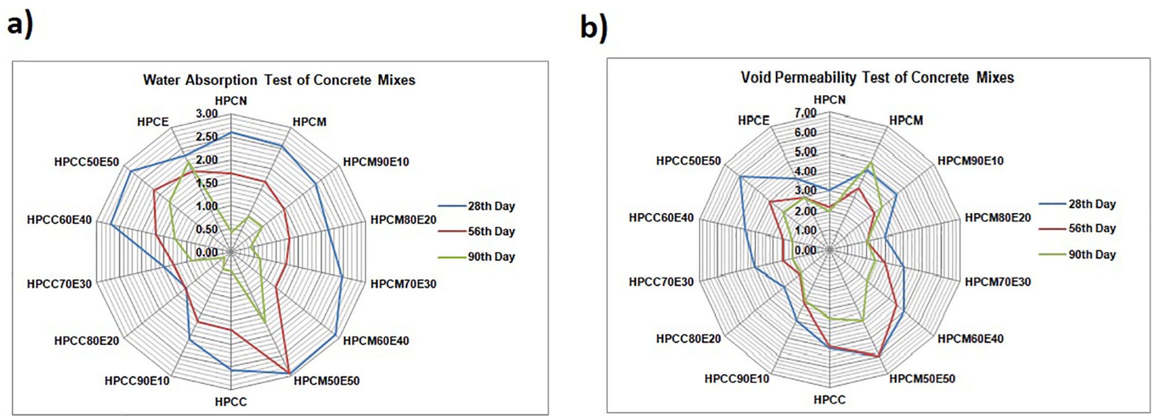

Figure 12: (a) Results of water absorption test of the HPC mixes. (b) Results of void permeability test of the HPC mixes.

The void permeability of concrete is primarily swayed by the paste phase and is largely related on the interconnected capillary pores within the paste. In this context, the high-performance concrete mix utilizing alternate fine aggregates demonstrated reduced interconnected capillary porosity within the paste, contributing to lower void permeability rates.

4.7.3. Acid resistance test

The acid resistance of concrete is an important aspect to evaluate its durability in environments where chemical exposure is a concern. The testing process involved subjecting concrete specimens to immersion in two different acid solutions: a 3% H_2SO_4 solution and a 3% HCl solution, while maintaining a constant pH level of 4 throughout the test duration. This controlled environment allowed for the assessment of how the concrete responded to chemical attack over time. Figure 13 presents acid resistance test results, showcasing the trend of mass loss over time. By analyzing the data, researchers can understand how the concrete performs under acidic environments and make informed decisions regarding its suitability for applications where acid exposure is a concern.

The maximum weight loss was observed for the HPCC50E50 mix at 90th day, reaching 4% in sulphuric acid. Conversely, the HPCC80E20 mix exhibited a lower weight loss of 1.5%, which was comparatively lower than the control mix with a 2.6% weight loss at 90th day in sulphuric acid. In the case of hydrochloric acid, the mix HPCM50E50 experienced the highest weight loss at 90th day. The HPCC80E20 mix showed a moderate weight loss of 0.1% at 90th day, which was comparatively lower than the control mix with a 1.4% weight loss at 90th day. Each mix demonstrated a variation in weight loss compared to the control mixes. The reduction in porosity of the concrete due to the addition of fibres and alternate fine aggregates was the main contributing factor to the decrease in weight loss.

4.8. Microscopic images and elemental identification

Scanning Electron Microscopy (SEM) is a technique that produces detailed, magnified images of an object by scanning its surface to create a high-resolution image. The resulting images provide information about the composition of the object and its physical features. The analytical technique known as Energy Dispersive X-ray Analysis (EDAX), used for the elemental analysis of a sample [28]. In this research, SEM and EDAX images were taken to analysis the surface morphology and the elemental analysis of the HPCs mix. Figure 14 shows the microscopic images and elemental identification of HPCs with Manufactured Sand (HPCM). Figure 15 shows the microscopic images and elemental identification of HPCs with CRF 80% with 20% Eco Sand (HPCC80E20).

The inference drawn from the Scanning Electron Microscope (SEM) images of the HPC mix indicated that more hydration products, specifically Calcium Silicate Hydrate (C-S-H), were visible present in the HPCC80E20 mix compared to the HPCM mix. Additionally, the Energy Dispersive X-ray Analysis (EDAX) results revealed that the amounts of calcium, alumina and silica were higher in the HPCC80E20 mix compared to the HPCM mix. The process of hydration involves the chemical reactions between water and cementitious materials, primarily cement, leading to the formation of hydration products in the HPC mix. Secondary reactions could occur more between the hydration products and unhydrated cement particles, especially due to the addition of Alccofine 1203, further contributing to the densification and strength development of concrete over time.

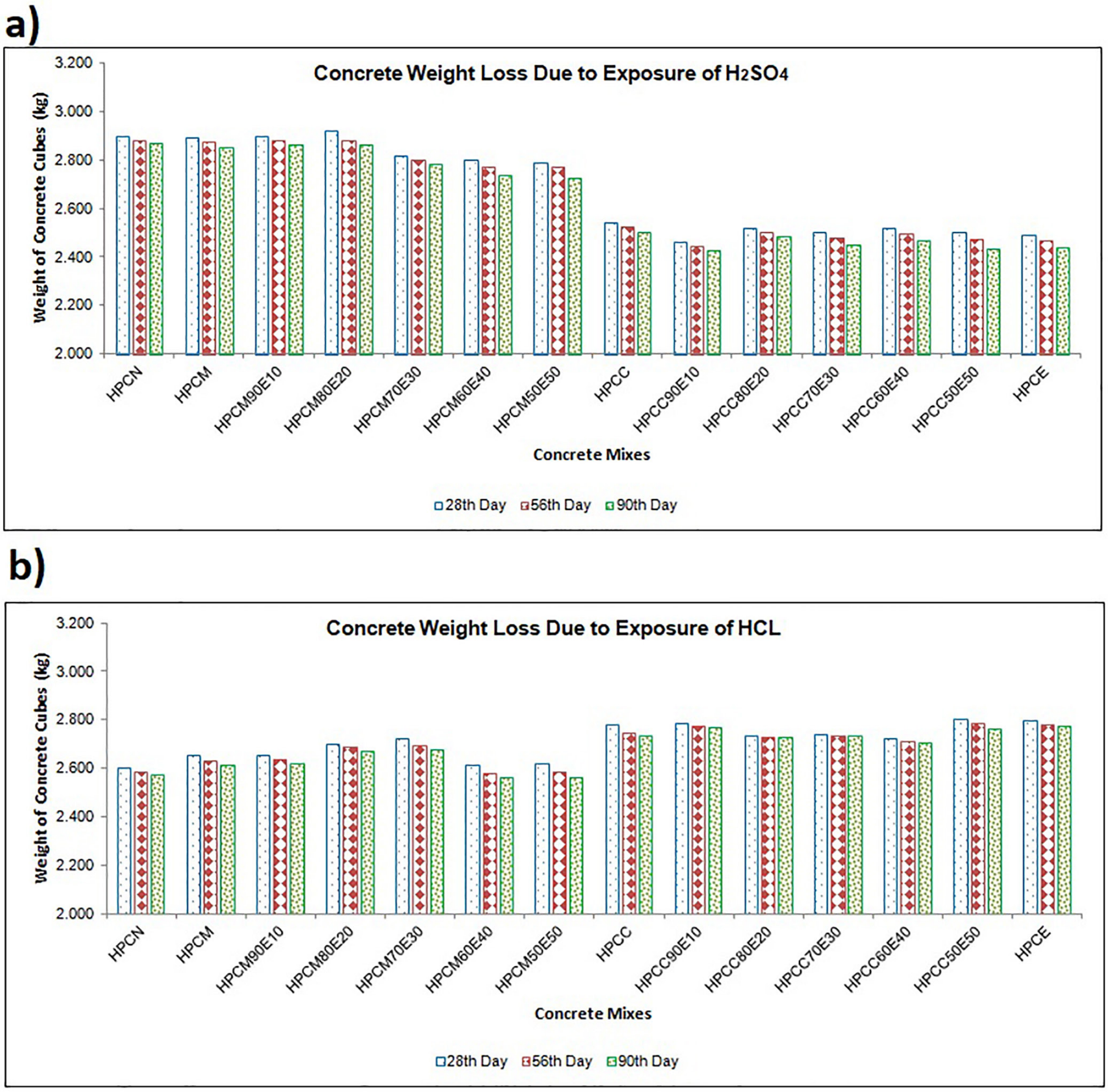

Figure 13: (a) Comparison of the HPC concrete mixes weight loss due to H_2SO_4 solution. (b) Comparison of the HPC concrete mixes weight loss due to HCl solution.

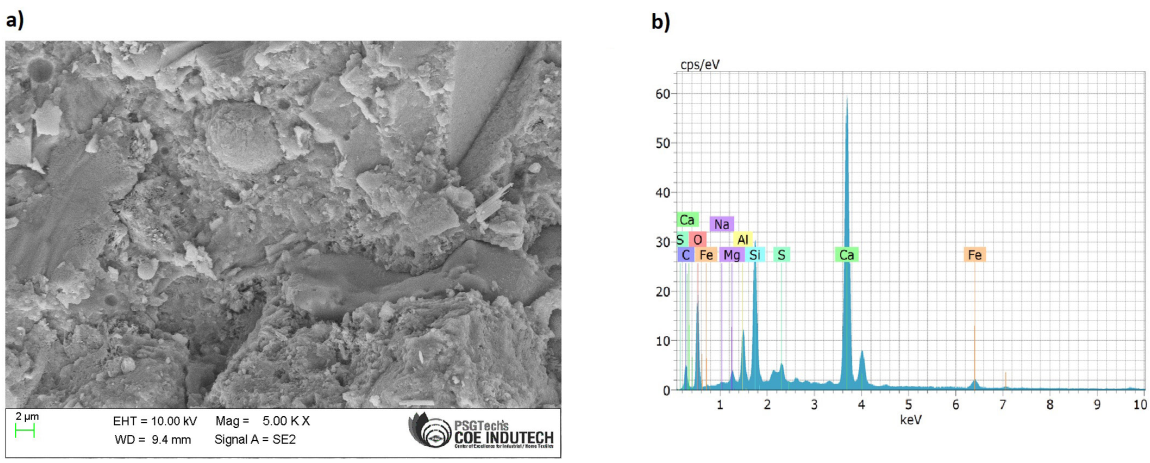

Figure 14: (a) FESEM image of HPCM. (b) EDAX results of HPCM.

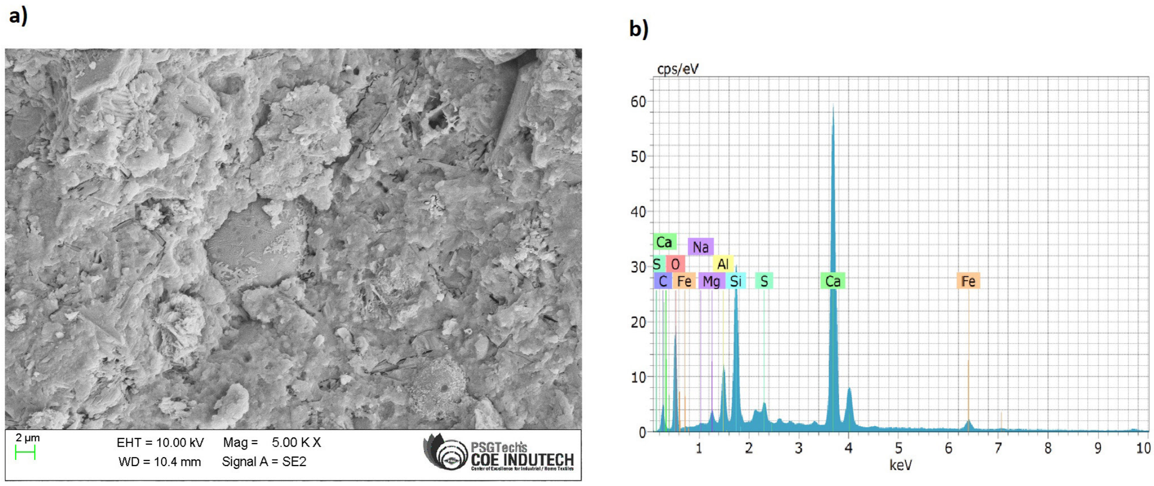

Figure 15: (a) FESEM image of HPCC80E20. (b) EDAX results of HPCC80E20.

4.9. Response Surface Methodology (RSM) model

Response Surface Methodology (RSM) refers to a set of statistical and mathematical tools used for creating empirical models. These techniques are employed to optimize a response, which is typically an output variable affected by multiple independent variables, often referred to as input variables. In RS, experiments are designed with precision, involving a series of tests or runs. These experiments systematically vary the input variables to determine how and why the output response changes. This method is instrumental in understanding and improving processes, systems, or products by exploring the relationship between input and output variables. Initially, RSM was developed with a focus on modelling experimental responses. Overtime, RSM evolved to encompass the modelling of numerical experiments. The key distinction lies in the nature of the error developed by the response data. When applied to design optimization, RSM aims to minimize the expenses associated with costly analysis methods such as the computational fluid dynamics analysis or finite element method, along with the numerical noise that often a accompanies them [29]. A critical component of RSM is the Design of Experiments (DoE). While these strategies were initially devised for fitting models to physical experiments, they are also adaptable for application in numerical experiments [30].

In this research work, the variables such as manufactured sand, crushed rock fines and eco sand were taken for the RSM model. By using the DoE approach, characteristic compressive strength and splitting tensile strength were compared with the experimental values. Figure 16 shows the contour plot of strength properties with various HPCs. Figure 17 shows the surface plot of strength properties with various HPCs.

The regression equation for calculating the characteristic compressive strength and splitting tensile strength of the concrete mix with manufactured sand and eco sand were,

$$\text{Compressive Strength} = 30.1 + 0.1390\,MS + 0.225\,ES - 0.000061\,MS * MS - 0.000132\,ES * ES - 0.000411\,MS * ES$$

$$\text{Splitting Tensile Strength} = 1.999 + 0.00902\,MS + 0.01895\,ES - 0.000004\,MS * MS - 0.000017\,ES * ES - 0.000029\,MS * ES$$

The regression equation for calculating the characteristic compressive strength and splitting tensile strength of the concrete mix with crushed rock fines and eco sand were,

$$\text{Compressive Strength} = 29.8 + 0.1377\,CRF + 0.284\,ES - 0.000065\,CRF * CRF - 0.000336\,ES * ES - 0.000387\,CRF * ES$$

$$\text{Splitting Tensile Strength} = 2.30 + 0.00910\,CRF + 0.01933\,ES - 0.000004\,CRF * CRF - 0.000019\,ES * ES - 0.000027\,CRF * ES$$

The contour plot of RSM is indeed a powerful tool for visualizing and understanding the effects of various factors on concrete properties. The above contour plot of RSM showed that the characteristic compressive strength and splitting tensile strength variations by adding the alternate fine aggregates such as manufactured sand, crushed rock fines and eco sand. By comparing the contour plots of compressive strength in figure 16 (a),

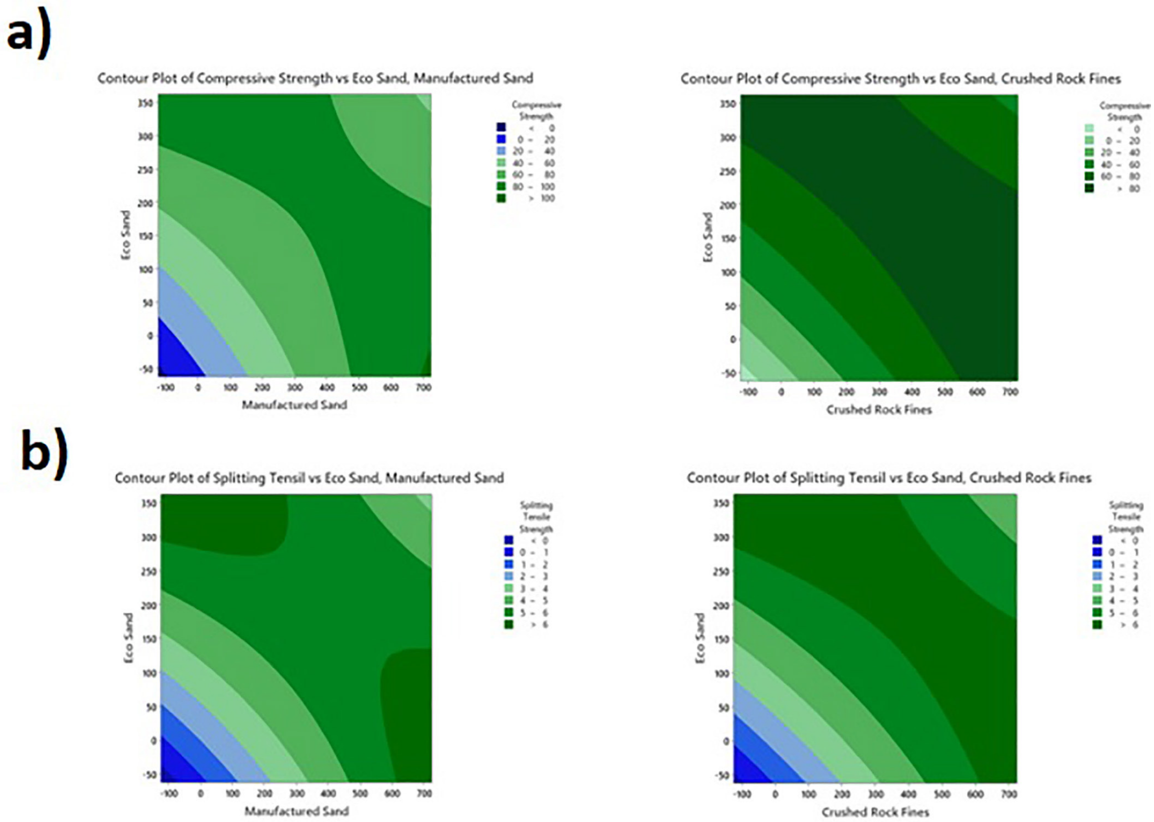

Figure 16: (a) Contour plot of compressive strength vs manufactured sand, crushed rock fines and eco sand. (b) Contour plot of splitting tensile strength vs manufactured sand, crushed rock fines and eco sand.

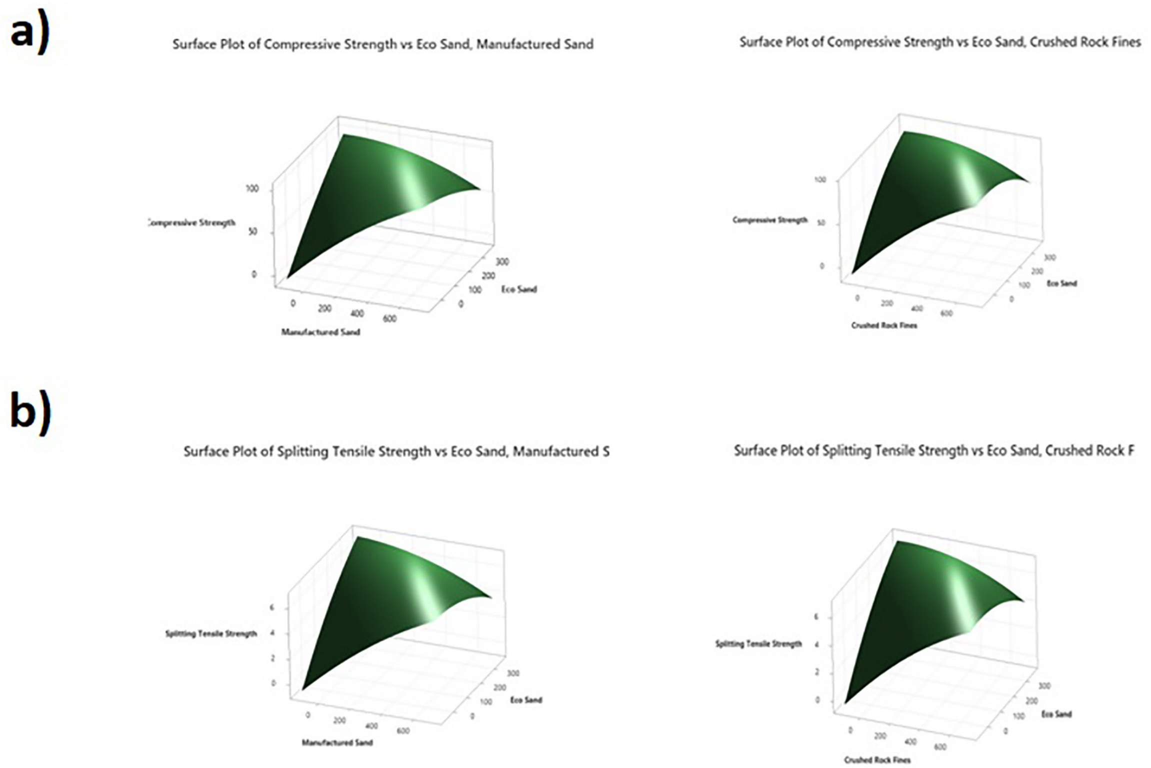

Figure 17: (a) Surface plot of compressive strength vs manufactured sand, crushed rock fines and eco sand. (b) Surface plot of splitting tensile strength vs manufactured sand, crushed rock fines and eco sand.

crushed rock fines with eco sand concrete mix showed better strength values and dark green patches with the manufactured sand and eco sand concrete mix showed lighter green patches. Similarly by comparing the contour plots of splitting tensile strength in figure 16 (b) crushed rock fines with eco sand concrete mix showed better strength values and dark green patches with the manufactured sand and eco sand concrete mix showed lighter green patches.

5. CONCLUSION

The conclusions observed from the experimental study were:

Before mixing of the HPC mix, sieve analysis conducted on alternative fine aggregates like crushed rock fines and eco sand, which can be employed as a partial substitute for manufactured sand. It is essential to eliminate dust particles from the crushed rock fines during the mixing process.

The workability of concrete was enhanced by the incorporation of Alccofine 1203, attributed to its ultrafine particle size. Conversely, the inclusion of glass fibres was observed to reduce the workability as it hampers the flow of concrete. The introduction of Alccofine 1203 resulted in enhancements in the mechanical properties of concrete. Notably, the inclusion of 10% Alccofine and crushed rock fines along with eco sand demonstrated strength gain of 5.62% more than the mixes of High-Performance Concrete with manufactured sand.

The concrete mix, High-Performance Concrete (HPC, comprising 80% crushed rock fines and 20% eco sand, exhibited superior compressive strength gain of 5.62%, splitting tensile strength gain of 9.02%, flexural strength gain of 5.65% and durability properties test results showed less permeable, less water absorption, resistance to acid attack compared to both the control mix and various other mix proportions.

The microscopic studies showed that more amount of calcium hydroxide content was developed and it again reacts with the alccofine ingredients, more amount of CSH gel would be formed and gaining the strength in the HPC mixes.

The regression equation derived from the RSM model played a crucial role in estimating and optimizing the compressive strength and splitting tensile strength values based on variations in the alternate fine aggregates.

The contour plot generated from the RSM model provided insights, where the mix containing crushed rock fines and eco sand showed dark patches. These dark patches indicated superior performance in terms of compressive strength and splitting tensile strength properties compared to the mix with the control (manufactured sand) and eco sand. This analysis highlights the effectiveness of using crushed rock fines and eco sand in improving the mechanical properties of the concrete mix.

The High-Performance Concrete (HPC) mix, incorporating different alternate fine aggregates for partial replacement, will be assessed and compared against existing test results.

Additionally, further durability studies, including carbonation, impact resistance and permeability can be performed on the HPC mix containing crushed rock fines and eco sand.

Behaviour of beams and columns under monotonic and cyclic loading can be conducted.

Further investigations can be carried out to evaluate how these materials perform in pre-cast concrete element applications.

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