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Evaluation of reactive powder concrete mechanical, durability, and microstructural properties under various exposure conditions

Govindh MadhavanKutty Ambika[1], Sunil Chemmankalayil Mani[1],
Sreekumara Ganapathy Venkadachalam Saraswathi[2], Sasikumar Palanisamy[3]

[1]Central Asian University, School of Architecture and Design. Mirzo-Ulugbek, Tashkent, Uzbekistan.
[2]AJOU University, Department of Civil Systems Engineering. Tashkent, Tashkent, Uzbekistan.
[3]K. Ramakrishnan College of Technology, Department of Civil Engineering. Tamil Nadu, India.
e-mail: m.ambika@centralasian.uz, c.sunil@centralasian.uz, kumar.sree@ajou.uz, sasiserene@gmail.com

ABSTRACT

Currently, the concrete structure is being developed using alternative materials, and the strength properties of the concrete have improved in various aspects. The coarse particles are removed from the concrete and the fine particles in the concrete. It tends to improve the mechanical and durability properties of the concrete in different environmental conditions. This research examined the mechanical and durability properties of the Reactive Powder Concrete (RPC) under environmental conditions. This study's primary objectives were to evaluate the RPC's compressive, split tensile and flexural strength. Additionally, the durability properties of the RPC were examined in various immersion conditions. The RPC is investigated by incorporating the glass fibre in various percentages of 0.1%, 0.2%, 0.3% and 0.4%, respectively. The optimum glass fibre 0.75% enhanced the mechanical properties of the RPC by 15%, 24% and 27% for compressive, split tensile and flexural strength compared to the conventional RPC mix. The durability properties of the RPC were improved by 23% compared to the conventional RPC mix subjected to acid resistance. Furthermore, microstructural analyses such as SEM and EDAX were evaluated for both the conventional and optimum mixes of RPC. These analyses help to examine the morphology and chemical components of RPC. Linear regression analysis was performed in this study to predict the mechanical properties of RPC. The relationships between compressive and split tensile strength, as well as compressive and flexural strength, showed a high correlation with the experimental results. The linear regression coefficient (R^2) is 0.96 for compressive and split tensile strength and 0.97 for compressive and flexural strength. This research can be recommended for practical applications in developing sustainable structures.

Keywords: Reactive powder concrete; Glass fibre; Micro-particles; Quartz powder; Silica fume.

1. INTRODUCTION

The concrete is being improved using various fine particle replacements for the coarse particles in concrete. The fine particles increased the strength and durability properties of the concrete. Reactive powder concrete is one of the alternative concrete to enhance the mechanical and durability properties of concrete structures. Fine particles are filled in the concrete voids, improving the strength and durability.

Ultra-High Strength Concrete (UHSC) is characterized by its exceptional mechanical properties and ultra-dense microstructure, providing advantageous waterproofing and durability. Incorporating high-volume mineral admixtures such as fly ash, ground granulated blast furnace slag, and silica fume has been shown to significantly enhance the compressive strength and durability of UHSC [1]. RPC has exceptional mechanical properties, including high compressive and flexural strength, toughness, and durability. Studies have shown that applying pre-setting pressure can significantly influence the mechanical properties of RPC. The research demonstrated that applying pre-setting pressure ranging from 5 to 25 MPa to RPC samples improved flexural strength and fracture toughness. The maximum flexural strength achieved was 36.4 MPa, and the toughness increased more than threefold under the highest pre-setting pressure of 25 MPa [2]. The optimized mixture significantly enhances the static mechanical properties of C200green RPC, such as compressive strength, flexural strength, and fracture energy. The compressive strength exceeds 200 MPa, flexural strength exceeds 60 MPa, and fracture energy reaches 30,000 J/m^2. Including steel fibres improves the fibre-matrix interfacial bonding strength, contributing to the overall mechanical performance [3].

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Incorporating hybrid fibres (steel and PVA) has been found to improve the compressive strength of RPC after high-temperature exposure. Steel fibres enhance the tensile strength and toughness, while polyvinyl alcohol fibres contribute to the ductility and energy absorption capacity. The optimal combination of these fibres can mitigate the adverse effects of high temperatures on compressive strength [4]. Adding Ground Granulated Blast Furnace Slag (GGBFS) to RPC improves its mechanical properties by refining the microstructure and enhancing the hydration process. Studies have demonstrated that RPC containing high volumes of GGBFS exhibits superior compressive strength, flexural strength, and toughness compared to conventional RPC. The denser microstructure resulting from the pozzolanic reaction of GGBFS contributes to these enhanced properties. RPC with high volumes of GGBFS also shows improved durability. The enhanced microstructure provides better resistance to aggressive environmental conditions, such as freeze-thaw cycles, chloride ion penetration, and sulfate attack. This makes GGBFS-enhanced RPC suitable for applications requiring long-term durability and minimal maintenance [5].

The addition of nano-zirconia particles to RPC improves its mechanical and electrical properties. Studies have demonstrated that RPC containing NZ exhibits superior compressive strength, flexural strength, and toughness compared to conventional RPC. The nano-scale of NZ particles contributes to a denser microstructure, enhancing the concrete's overall performance. The reinforcing mechanisms of NZ in RPC are studied through various analytical techniques, including thermogravimetry (TG) analysis, scanning electron microscope observation, and X-ray powder diffraction analysis. These studies reveal that NZ particles accelerate the formation of C-S-H gel, leading to increased compressive strength1. Additionally, NZ particles improve the interfacial bonding between the cement matrix and the fibres, enhancing mechanical properties [6]. Steel fibres have been found to improve the tensile performance of hybrid fibre-reinforced RPC significantly. They enhance the tensile strength and toughness, providing better resistance to high temperatures. On the other hand, polypropylene fibres do not have a noticeable effect on the tensile properties [7].

High-performance concrete (HPC) is a highly advanced form of concrete that exhibits superior mechanical properties, including high compressive strength, durability, and resilience. Including fibres, such as steel, polypropylene, or glass fibres, further enhances these properties. This review examines the compressive behaviour of fibre-reinforced HPC when subjected to elevated temperatures [8]. Reactive Powder Concrete RPC is a UHPC known for its superior mechanical properties, including high compressive strength and significant ductility. This review examines the properties, preparation methods, and applications of RPCs with compressive strengths ranging from 200 to 800 MPa and enhanced ductility [9]. UHPC exhibits remarkable compressive strength, often exceeding 200 MPa, and tensile strength around 9 MPa. These properties make UHPC suitable for critical infrastructure applications where high load-bearing capacity is essential. The high elastic modulus of UHPC, typically around 52.4 GPa, contributes to its stiffness and load-bearing efficiency. The long-term stability of UHPC is characterized by minimal creep and shrinkage, ensuring structural integrity over time. This stability is crucial for applications in bridges and other infrastructure projects where long-term performance is a priority [10].

The incorporation of ZrO_2 nanoparticles leads to a denser microstructure in cementitious composites. This densification results from the nanoparticles filling voids and promoting better bonding between cement particles. Scanning electron microscope analysis has revealed a more compact and uniform microstructure in composites containing ZrO_2 nanoparticles, contributing to their enhanced mechanical properties. The alternative materials in reactive powder concrete ZrO_2 (zirconium dioxide) and Ground Granulated Blast Furnace Slag (GGBFS). For instance, ZrO_2 is noted for its durability enhancement, while GGBFS is recognized for reducing the carbon footprint and improving mechanical properties [11]. Reactive powder-based concretes offer exceptional mechanical properties and durability, making them suitable for various demanding applications. The hybrid use with OPC presents a cost-effective solution for projects requiring high performance and economic feasibility [12]. Assessing the shrinkage and water permeability of RPC produced in Hong Kong is essential for ensuring its long-term performance and durability. Proper mix design, curing techniques, and fine powders contribute to low shrinkage and permeability, enhancing the material's suitability for demanding construction applications [13]. Optimized mix design and curing conditions are essential for maximizing the performance of reactive powder concrete. Key factors such as particle packing density, water-to-cement ratio, silica fume content, and fibre incorporation must be carefully considered. Advanced techniques like steam and autoclave curing can further enhance RPC's mechanical properties and durability [14]. The curing and autoclaving process parameters are critical in determining the final properties of reactive powder concretes. Optimized parameters yield superior mechanical properties and durability, making RPC suitable for high-performance applications [15]. The compressive strength of Reactive Powder Concrete (RPC) is influenced by a variety of factors, including material choice, curing techniques, and mixing processes. By optimizing these elements, the durability and performance of RPC can be significantly enhanced for use in infrastructure and high-performance structures [16]. RPC made from dune sand and subjected to hot air curing shows encouraging mechanical and microstructural characteristics. The synergistic effect of carefully selected aggregates and accelerated curing processes leads to improvements in compressive strength, durability, and microstructural quality [17]. Additionally, the development of compressive strength in dune sand-based RPC varies with the curing method used. Optimized curing conditions promote better hydration kinetics, enhance microstructural refinement, and improve both early-age and long-term mechanical properties [18].

The curing regime significantly influences reactive powder concrete's mechanical properties and durability. Autoclave curing produces the highest compressive, flexural, and tensile strengths and superior durability due to the densest microstructure. Steam curing also enhances these properties but to a lesser extent. While effective, standard curing results in lower mechanical performance than advanced curing techniques [19]. The experimental investigation of RPC exposed to elevated temperatures reveals a substantial decline in mechanical properties, particularly at temperatures exceeding 400°C. The occurrence of spalling and microstructural degradation further complicates its use in high-temperature environments [20]. Combining coir pith aggregates and pyrogenic silica offers a sustainable alternative to traditional RPC mix designs. The internal curing ability of coir pith aggregates helps reduce shrinkage, while pyrogenic silica enhances particle packing density and durability. This eco-friendly approach provides a cost-effective solution for producing high-performance concrete. The investigation demonstrates that sustainable steel fibre-reinforced RPC utilizing coir pith aggregates and pyrogenic silica can achieve mechanical and durability properties comparable to conventional RPC. This approach reduces environmental impact and offers economic benefits [21].

According to the research, many studies have been conducted using various fine particles and (micro & macro) fibres. The short micro-fibre achieved superior strength compared to the long fibre; this research gap has been identified and is the focus of this study. This study investigated RPC mechanical and durability properties by incorporating glass fibre at various percentages: 0.25%, 0.50%, 0.75%, and 1%. The mechanical properties show superior improvement with the addition of glass fibre. Additionally, the fine particles of silica fume, quartz sand, and quartz powder fill the voids of the RPC, which tends to improve the overall performance of the concrete. The primary objectives of this research is to examine the mechanical and durability properties of RPC. Additionally, microstructural analysis was conducted on both conventional and optimum RPC mixes. Numerous studies have investigated the role of micro steel fibres and fine particles in RPC. The present study evaluates RPC under various exposure conditions using fine materials such as silica fume, quartz sand, quartz powder, and glass fibre. The current methodology was chosen for this study because of its proven effectiveness in assessing RPC's mechanical, durability, and microstructural characteristics across different exposure scenarios. This method yields accurate results and is consistent with earlier research, facilitating comparability. Furthermore, it enables a thorough evaluation of fine materials like silica fume, quartz sand, quartz powder, and glass fiber, which are essential for enhancing RPC performance. The advantages and limitations of the present research are discussed as follows.

Advantages:

- **High Precision**: The model accurately forecasts mechanical properties that strongly correlate with experimental findings.
- **Dependable Performance**: The regression analysis offers a structured method for comprehending strength relationships.
- **Enhanced Material Efficiency**: It aids in optimizing mix ratios for better durability and mechanical strength.
- **Versatility**: The model is applicable for further research on RPC under diverse exposure scenarios.

Limitations:

- **Reliance on Experimental Data**: Its accuracy is contingent upon the quality of experimental data.
- **Narrow Focus**: The model may not adequately reflect the impacts of prolonged exposure conditions beyond the analyzed period.
- **Challenges in Adjustment**: Modifications to mix designs may necessitate further validation.
- **Risk of Overfitting**: The regression model might not perform well under different conditions without careful validation.

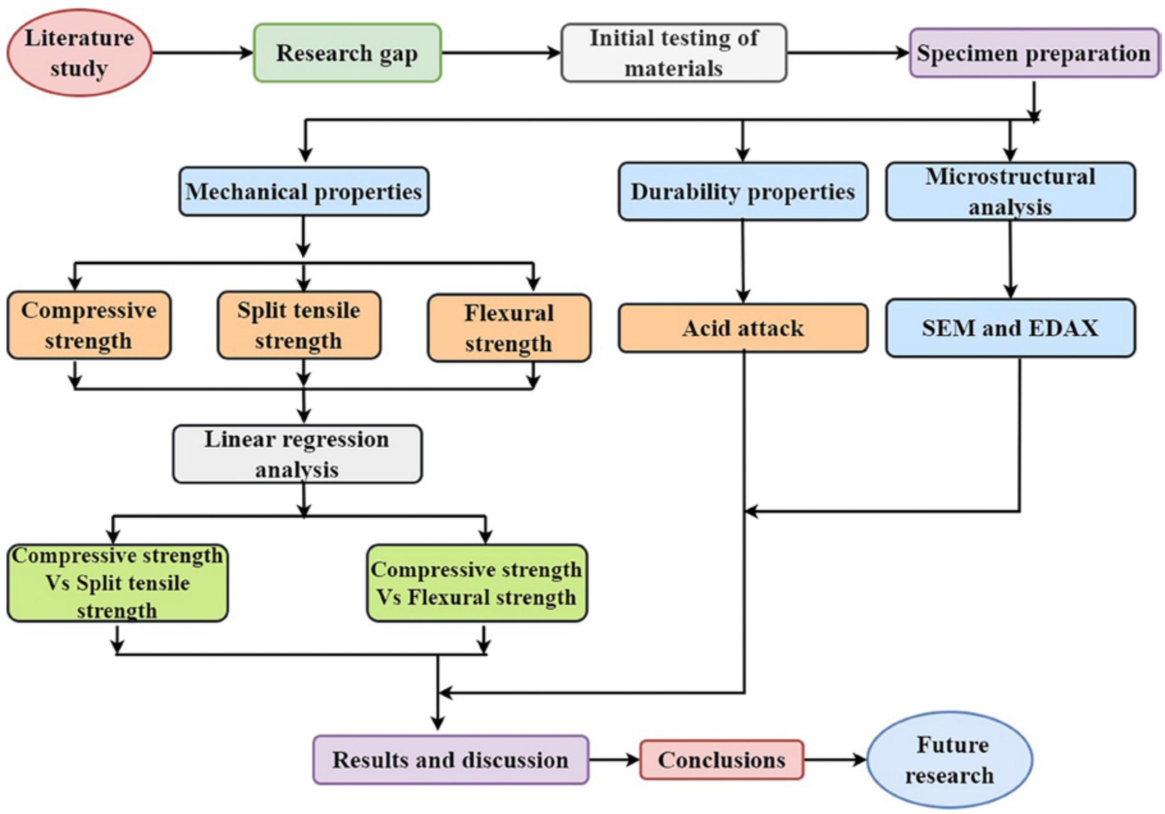

Figure 1: Methodology of this study.

The flow of the research methodology is shown in Figure 1. The research highlights are mentioned as follows:

- The micro-particles were used to investigate the RPCs mechanical, durability, and microstructural properties.
- The compressive, split tensile and flexural strength was enhanced by 15%, 24% and 27% for optimum RPC mix.
- The mechanical and durability properties of the RPC with glass fibres are experimentally studied.
- The addition of glass fibre in the RPC mix improved the concrete's strength properties in various aspects.
- Similarly, in the case of acid attack, the strength properties declined by 5%, 10% and 15%, respectively, for 56, 90 and 10 days.
- This RPC research project proposed a practical application to improve the durability of concrete structures.

2. EXPERIMENTAL STUDY

2.1. Materials

Reactive powder concrete is made with Ordinary Portland Cement (OPC), the primary binder. To attain the remarkable characteristics of RPC, it is frequently blended with supplementary cementitious materials, including quartz powder and silica fume. Incorporating these materials significantly improves the strength and long-term durability of RPC. Utilize glass fibres to lessen environmental impact. Limit the proportion of glass fiber in the mixture to preserve structural integrity, as an overabundance can elevate costs and environmental strain. Adopt energy-efficient steam curing systems to decrease energy usage. Employ renewable energy sources for steam production to minimize carbon emissions [22]. The fine particles of quartz powder and silica fume fill the voids in concrete, enhancing its strength and durability. The cement is partially replaced with cementitious materials such as quartz powder and silica fume by 10%. The physical properties of the quartz powder and silica fume are examined and reported in Table 1.

Table 1: Physical properties of the materials.

PHYSICAL PROPERTIES	CE	SF	QP	QS	SP
Initial setting time (Mins)	38	–	–	–	–
Final setting time (Mins)	278	–	–	–	–
Fineness modulus (%)	2.34	2.65	2.87	3.62	–
Specific gravity (g/cc)	3.12	2.18	2.54	2.64	1.02

Water content is another essential factor in improving the strength properties of the concrete. The chemical admixture increases the workability of the concrete and reduces the water content. The chemical admixture improves the strength properties of the concrete and requires a low water-cement ratio in the concrete mix. In this study, the chemical admixture used is Conplast SP-430, with its physical properties given in Table 1.

The reactive powder concrete with fine particles such as quartz sand, silica fume, and quartz powder is demonstrated in Figures 2(a)–(c). The glass fibre is bonded to the cement paste and aggregates, enhancing the mechanical properties of the reactive powder concrete, as shown in Figure 2(d). Similarly, the particle size distribution of the supplementary materials is displayed in Figure 3. The physical properties of glass fibre are reported in Table 2.

2.2. Mix proportion and preparation of the RPC

The RPC mix proportion is designed [2, 4], and based on the trial mix studies, the mix proportion of the RPC is presented in Table 3. The main objectives for the mix proportion are the properties of the materials, target compressive strength of the RPC, and trial mix compositions. The trial mix study mix proportion gives superior results to the target compressive strength.

The preparation of the RPC is a crucial part of achieving the target compressive strength of the RPC. Initially, the dry cementitious materials are placed in the machine mix drum. The materials are slowly mixed for two minutes, then the water and chemical admixtures are added. The RPC mix is continuously mixed to achieve good consistency and homogeneity. Finally, the glass fibre is added. The concrete mix is continually mixed for 10 minutes with uniform consistency to ensure the glass fibre is distributed throughout the mix. The RPC mix is dumped into a steel tray and poured into moulds to prepare the cubes, cylinders, and prisms. All RPC samples are prepared with uniform compaction to avoid the formation of a honeycomb structure in the concrete. The RPC samples are placed at room temperature for 24 hours. The next day, the samples are removed from the moulds and placed for curing.

The RPC samples are cured in steam to achieve the target compressive strength. The samples are kept in an oven at 200°C for three days. Many studies have examined the mechanical properties of RPC under steam and water curing conditions; these curing conditions enhance the strength properties of RPC [23, 24]. Steam curing improves C-S-H gel formation, which tends to increase the strength properties of RPC. Three samples are prepared and cured in steam at various ages in each mix.

3. RESULTS AND DISCUSSION OF THE RPC

3.1. Compressive strength

The compressive strength of the RPC is enhanced using fine particles as an alternative to coarse materials. These fine particles provide proper consistency and improved strength properties to the RPC. The optimum materials produce superior performance in RPC [12, 13, 25–29]. The RPC strength properties are enhanced by incorporating silica fume, quartz powder, and quartz sand in the RPC mix. The fine particles fill the voids, which tend to improve the mechanical properties of the RPC. The compressive strength of the RPC is examined at 7 and 28 days, as reported in Table 4. The RPC is an advanced cementitious material known for its exceptional mechanical properties, particularly its high compressive strength. The composition of RPC, typically including silica fume, quartz powder, quartz sand, and glass powder, contributes to its superior performance. The statistical analysis and experimental results are reported in Table 5.

The conventional concrete mix of RPC without any glass fibre (GF0) exhibits a compressive strength of 175.42 MPa. This demonstrates the inherent strength of the mix comprising silica fume, quartz powder, and quartz sand. Effect of Glass Fiber. Adding glass fibre to the RPC mix shows a clear trend of increased compressive strength. At 0.25% glass fiber (GF0.25), the compressive strength increases to 179.54 MPa. At 0.5% glass

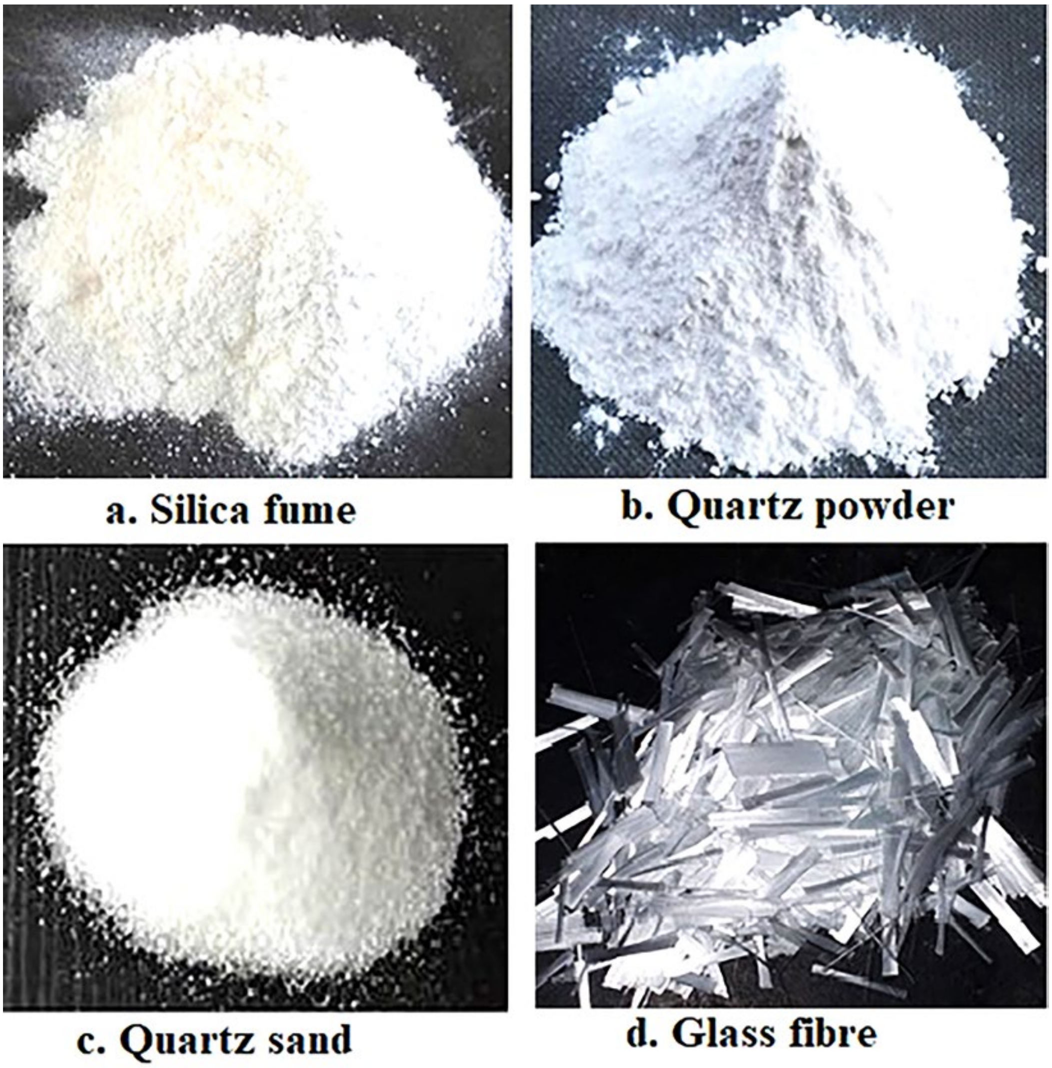

Figure 2: Reactive powder concrete materials.

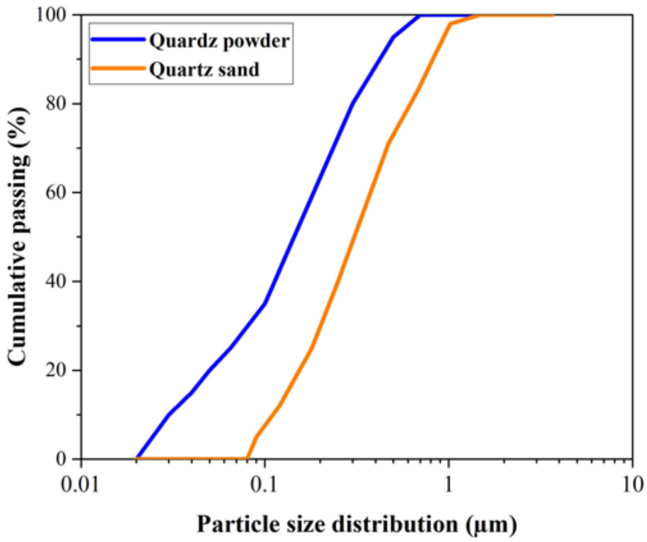

Figure 3: Particle size distribution of the quartz powder and quartz sand.

Table 2: Physical properties of the glass fibre.

PHYSICAL PROPERTIES	GLASS FIBRE
Specific gravity (g/cc)	2.71
Density (kg/m^3)	2.41
Modulus of elasticity (GPa)	29.50
Tensile strength (MPa)	6.42
Length (mm)	12
Diameter (μm)	3

Table 3: Mix proportion of the RPC (kg/m^3) for 1m^3.

CEMENT	SILICA FUME	QUARTZ POWDER	QUARTZ SAND	SP	W	GF (%)	W/C
748	204	327	854	36	226	0.25–1	0.24

Table 4: Mechanical properties of the RPC.

MIX ID	CS (MPa)		STS (MPa)		FS (MPa)	IMPROVED STRENGTH AT 28 DAYS (%)		
	7 DAYS	28 DAYS	7 DAYS	28 DAYS	28 DAYS	CS	STS	FS
GF0	103.58	175.42	12.98	20.19	29.42	–	–	–
GF0.25	108.63	179.54	14.36	22.36	32.47	2.35	10.75	10.37
GF0.5	112.78	182.67	17.24	24.87	36.59	4.13	23.18	24.37
GF0.75	126.24	187.24	21.36	27.84	39.42	6.74	37.89	33.99
GF1	119.62	185.72	20.17	25.42	37.26	5.87	25.90	26.65

Table 5: Statistical analysis of the RPC.

MIX ID	EXPERIMENTAL RESULTS (MPa)			STATISTICAL RESULTS (MPa)			RATIO = ST/EXPT		
	CS	STS	FS	CS	STS	FS	CS	STS	FS
GF0	175.42	20.19	29.42	175.85	20.088	29.4723	1.00	0.99	1.00
GF0.25	179.54	22.36	32.47	179.30	22.58	32.89	1.00	1.01	1.01
GF0.5	182.67	24.87	36.59	183.28	24.47	35.49	1.00	0.98	0.97
GF0.75	187.24	27.84	39.42	188.00	27.23	39.28	1.00	0.98	1.00
GF1	185.72	25.42	37.26	184.16	26.31	38.02	0.99	1.04	1.02
Mean							1.00	1.00	1.00
Standard deviation							0.005	0.023	0.019
Coefficient of variation							0.52	2.29	1.94

fiber (GF0.5), the strength further rises to 182.67 MPa. The highest compressive strength is observed at 0.75% glass fiber (GF0.75), with a value of 187.24 MPa. Including glass fibers enhances the mechanical properties by providing additional reinforcement within the concrete matrix. This reinforcement helps to bridge micro-cracks and improve the overall load-bearing capacity of the RPC. At 1% glass fiber (GF1), the compressive strength slightly decreases to 185.72 MPa. This suggests that while adding glass fibers generally improves compressive strength, there is an optimal content level (0.75%) beyond which the benefits may diminish. The slight reduction at GF1 could be due to fiber agglomeration or reduced mix workability. The compressive strength of RPC is significantly influenced by the addition of glass fibers. The data indicates that the optimal amount of glass fiber for maximizing compressive strength is around 0.75%. Including glass fibers enhances RPC's mechanical properties, making it a suitable material for applications requiring high strength and durability. Understanding the optimal fiber content is crucial for the practical application of RPC in developing sustainable and high-performance structures.

The compressive strength of the RPC increased with the mixed composition of quartz sand and powder [18]. The compressive strength of the RPC at 28 days improved by 2.35%, 4.13%, 6.74%, and 5.87% with the addition of glass fibre at 0.25%, 0.50%, 0.75%, and 1%, respectively, compared to the control RPC, as shown in Figure 4. Similarly, the compressive strength of the RPC was evaluated and achieved at 100 MPa at 28 days [14]. During testing, the cube samples without glass fibre failed suddenly, while the optimum RPC mix failed gradually compared to the control RPC sample. According to the experimental study, the optimum mix proportion was 0.75% glass fibre. The RPC samples exhibited brittle behaviour without fibre, while the RPC samples with fibre failed with ductile behaviour.

3.2. Split tensile strength

The split tensile strength of the RPC is determined at 7 and 28 days, as presented in Table 4. The split tensile strength of the RPC improved at 28 days by 10.75%, 23.18%, 37.89%, and 25.90% compared to the control concrete samples, as displayed in Figure 5.

The glass fibre plays a significant role in improving the split tensile strength of the RPC at various percentages: 0.25%, 0.50%, 0.75%, and 1%. Incorporating silica fume and quartz powder significantly enhances RPC's compressive and flexural strength. This improvement is attributed to their pozzolanic characteristics, enabling them to interact with calcium hydroxide present in the concrete, forming additional calcium silicate hydrate (C-S-H), which serves as the primary binding agent in concrete. Linear regression analysis was conducted to examine the relationship between the compressive and split tensile strength of reactive powder concrete.

Regression analysis is a statistical method used to examine the relationship between dependent and independent variables. In this case, the CS and STS of reactive powder concrete were analyzed using linear regression. The R^2 value of 0.96 indicates a very strong correlation between CS and STS, as shown in Figure 6. This high R^2 value suggests that approximately 96% of the variation in STS were explained by the changes in CS, implying a reliable predictive relationship. The strong linear relationship suggests that STS can be accurately predicted using CS values. The remaining 4% of variation may be due to external factors such as material inconsistencies, curing conditions, or measurement errors. The high predictability makes this regression model valuable for engineers designing high-performance RPC with optimized mechanical properties.

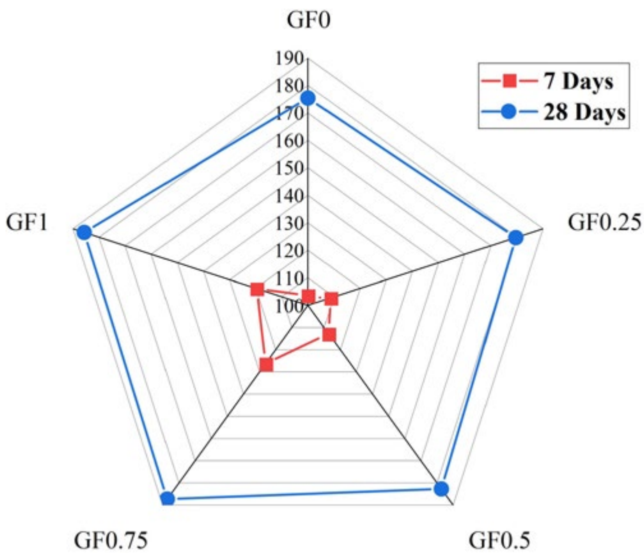

Figure 4: Compressive strength of the RPC at various ages.

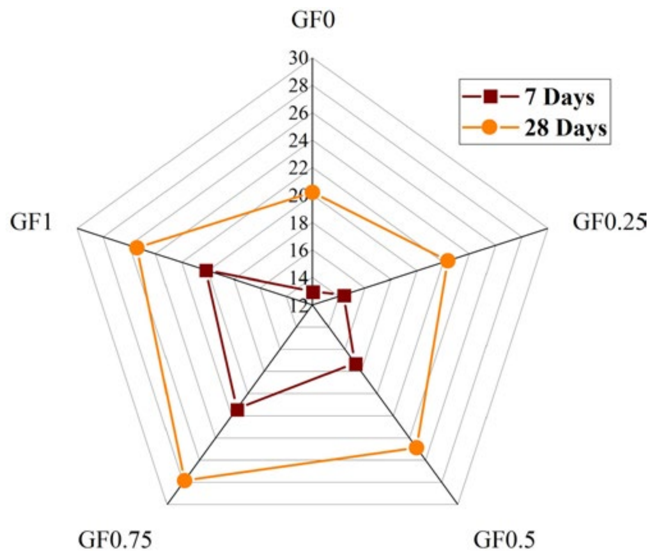

Figure 5: Split tensile strength of RPC at various ages.

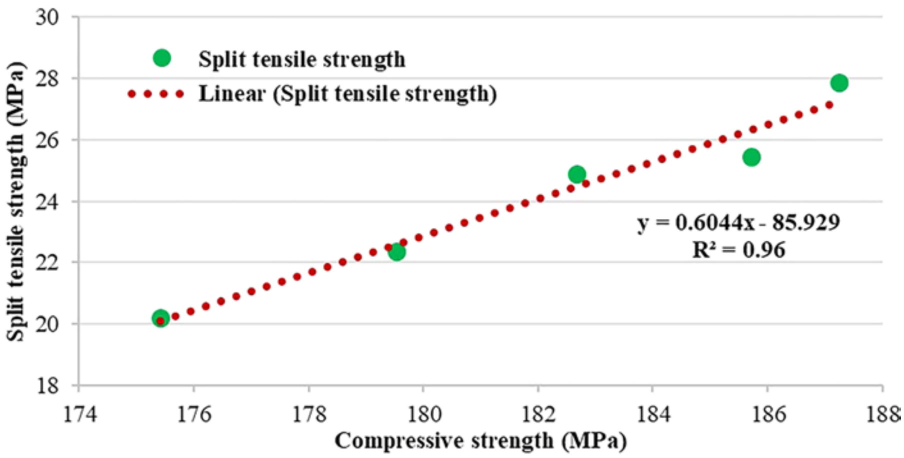

Figure 6: Regression analysis for compressive and split tensile strength.

3.3. Flexural strength

The flexural strength of the RPC is examined after the 28-day curing period is completed, is reported in Table 4. The determined flexural strength is depicted in Figure 7. All RPC samples are cured under steam curing conditions. Steam curing improves the hydration process of the C-S-H gel formulation's cementitious materials. The control RPC sample (without glass fibre) flexural strength is 29.42 MPa. Meanwhile, the flexural strength gradually improved 32.47 MPa, 36.59 MPa, 39.42 MPa and 37.26 MPa, with the addition of the glass fibre at 0.25%, 0.5%, 0.75% and 1.0%, respectively. The glass fibre tends to improve the RPC flexural strength by 10.37%, 24.37%, 33.99% and 26.65%, respectively, compared to the control RPC sample. Similar research was carried out using brass-coated steel fibre, and 15 MPa and 21.8 MPa achieved flexural strength at 28 days [6]. In addition to the glass fibre in RPC samples, the ductility and energy absorption capacity are improved compared to the control samples. Furthermore, the glass fibre prevents wide cracks and gradually fails compared to the control RPC samples. An R^2 value of 0.97 indicates a very strong correlation between CS and FS, as depicted in Figure 8. This implies that 97% of the variability in FS can be explained by changes in CS, demonstrating that

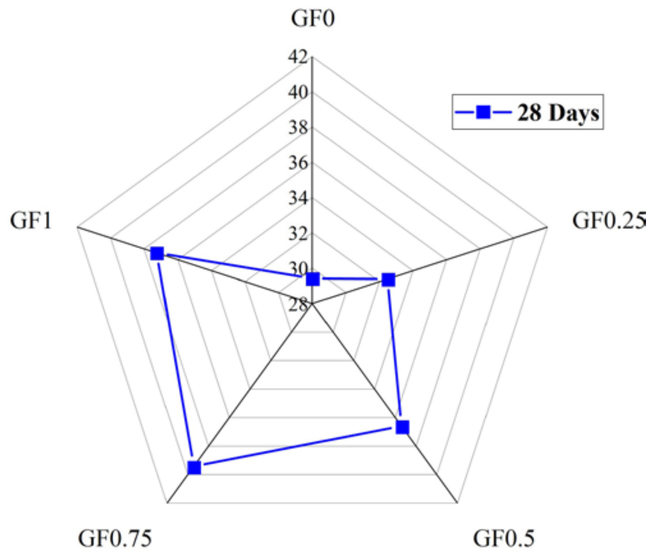

Figure 7: Flexural strength of concrete at various ages.

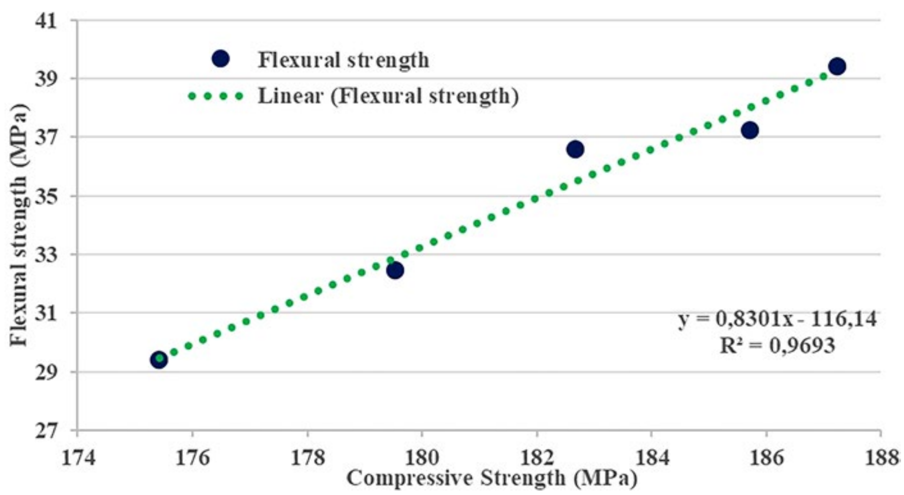

Figure 8: Regression analysis for compressive and flexural strength.

CS is a dependable predictor of FS. The elevated R^2 value points to a nearly linear relationship, allowing for precise estimations of FS based on CS. The remaining 3% of variability may stem from microstructural variations, curing processes, material discrepancies, or external factors. The regression analysis validates the strong correlation between CS and FS, enabling accurate predictions of FS from CS. This insight is particularly beneficial for structural engineers aiming to enhance the mechanical performance of RPC. Future research could investigate how different curing techniques and material variations impact this correlation.

3.4. Acid attack

The durability properties of the RPC are examined at 28, 56, and 90 days, as presented in Table 6 and in Figure 9. The losses in compressive strength and weight are determined at 28, 56, and 90 days, as displayed in Figures 10 and 11. All RPC samples (GF0, GF0.25, GF0.5, GF0.75, and GF1) are examined for durability properties under immersion in acid for 28, 56, and 90 days, respectively. The RPC samples are immersed in 5% sulfuric acid diluted in water. The compressive strength is compared to that of usually cured water RPC samples. The cube samples experience a reduction in strength and weight during acid immersion at 28, 56, and 90 days, respectively. According to the experimental study, 0.75% glass fibre improves the mechanical and durability properties of the RPC sample in various aspects. Compared to normal water curing, the compressive strength decreases by 0.44%, 1.61%, and 2.46% at 28, 56, and 90 days of acid immersion. Similarly, compared to standard water curing, the weight loss is 2.18%, 3.42%, and 4.68% at 28, 56, and 90 days of acid immersion. In another research, the compressive strength and weight are lost during acid immersion using brass-coated micro steel fibre, with periods of 10, 20, and 30 days, respectively. Silica fume, quartz powder and quartz sand improve RPC durability

Table 6: Durability properties of the RPC.

MIX ID	CS (MPa)	ACID IMMERSION (MPa)			DECREASED CS (%)		
	28 DAYS	28 DAYS	56 DAYS	90 DAYS	28 DAYS	56 DAYS	90 DAYS
GF0	175.42	172.36	170.25	168.52	1.78	3.04	4.09
GF0.25	179.54	178.24	176.48	175.36	0.73	1.73	2.38
GF0.5	182.67	181.69	179.67	178.54	0.54	1.67	2.31
GF0.75	187.24	186.42	184.28	182.75	0.44	1.61	2.46
GF1	185.72	184.74	182.42	180.69	0.53	1.81	2.78

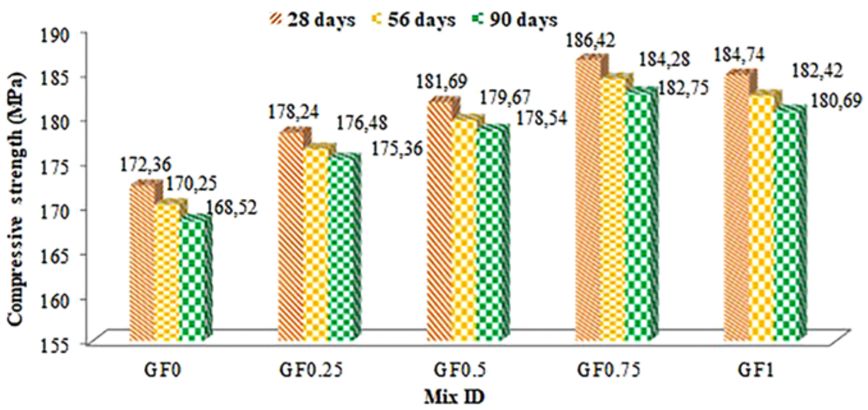

Figure 9: Comparison of the compressive strength of the RPC to acid attack at various ages.

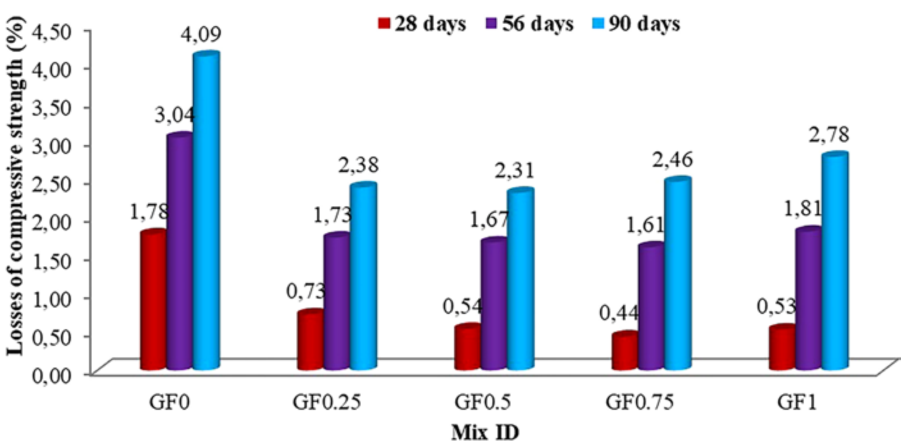

Figure 10: Losses of the compressive strength of the RPC subjected to acid attack.

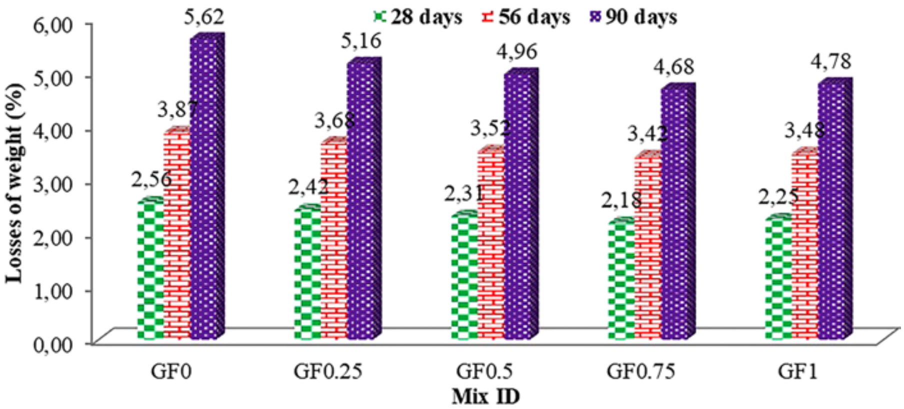

Figure 11: Losses of the weight to acid resistance for RPC.

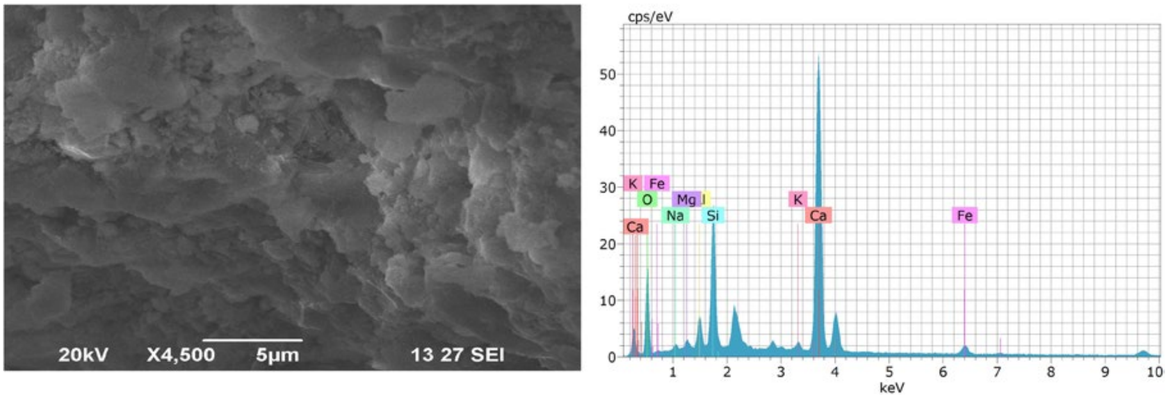

Figure 12: SEM and EDAx analysis of the RPC mix GF0.

by decreasing its permeability, thereby providing better protection against harsh environmental elements such as chlorides, sulfates, and other detrimental chemicals. Additionally, silica fume contributes to a more cohesive concrete mix, reducing the likelihood of segregation. Nevertheless, it may also lead to decreased workability, which often necessitates the incorporation of superplasticizers to ensure the mix remains workable [17].

3.5. Microstructural analysis

The microstructural analysis of the concrete is examined for the conventional and optium mix, the analysis include the Scannining Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDAX) as displayed in Figures 12 and 13. The SEM analysis of the RPC samples reveals the microstructural characteristics of the RPC. The micrographs show a dense and compact matrix with well-distributed silica fume and quartz powder particles. The presence of glass fibres can be observed, providing reinforcement and enhancing the mechanical properties of the concrete. The quartz sand particles are embedded within the matrix, contributing to the overall strength and durability of the RPC. In the conventional concrete mix (GF0), the microstructure appears less dense compared to the optimum mix concrete (GF0.75). The SEM images of GF0 show more voids and microcracks, which can be attributed to the lower content of glass fibres. On the other hand, the SEM images of GF0.75 exhibit a more uniform and compact microstructure with fewer voids and microcracks. This improvement in the microstructure can be linked to the higher content of glass fibres, which provide better reinforcement and reduce the formation of defects [30].

The EDAX analysis provides the elemental composition of the RPC samples. The spectra obtained from the EDAX analysis show the presence of key elements such as silicon (Si), oxygen (O), calcium (Ca), and aluminium (Al). These elements are primarily derived from the silica fume, quartz powder, and cement used in the RPC mix. In the conventional concrete mix (GF0), the elemental composition indicates a lower concentration

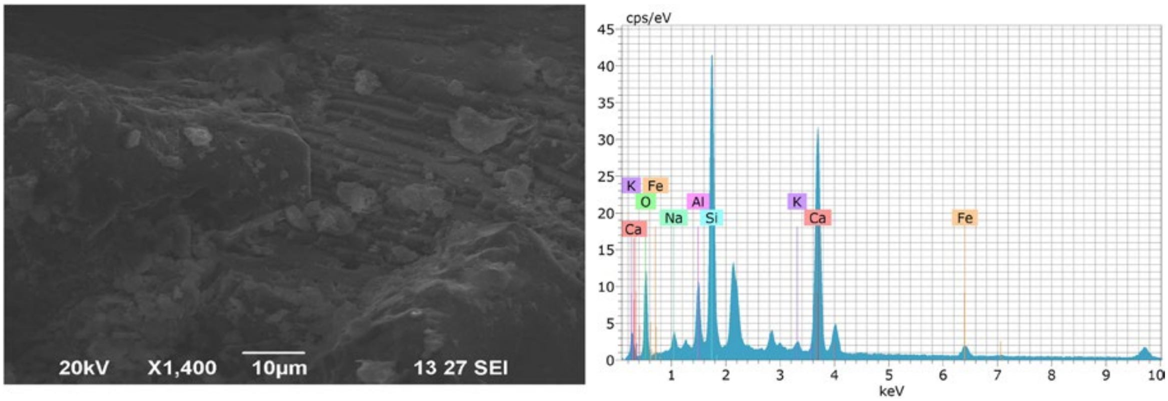

Figure 13: SEM and EDAx analysis of the RPC mix GF0.75.

of silicon and calcium compared to the optimum mix concrete (GF0.75). This difference can be attributed to the lower content of silica fume and glass fibres in GF0. The higher concentration of silicon and calcium in GF0.75 suggests a better distribution of silica fume and improved hydration of the cement, leading to enhanced mechanical properties.

The mechanical properties of the RPC samples are significantly influenced by their microstructural characteristics. The compressive strength of the conventional concrete (GF0) is 175.42 MPa, while the optimum mix concrete (GF0.75) exhibits a higher compressive strength of 187.24 MPa. This increase in compressive strength can be attributed to the improved microstructure and better reinforcement provided by the higher content of glass fibres in GF0.75.

4. CONCLUSIONS

The present research has been completed for experimental investigation of the mechanical and durability properties of the RPC subjected to standard and acid immersion at various ages. According to the experimental study, the following conclusions are drawn:

- Micro-fine particles such as silica fume, quartz powder, and quartz sand improve the mechanical and durability properties of the RPC by adding the optimum glass fibre of 0.75%.
- Compared to the control RPC sample, the compressive strength of the RPC is improved by 2.35%, 4.13%, 6.74%, and 5.87%, respectively, with the addition of the glass fibre.
- Similarly, the split tensile strength of the RPC sample is increased by 10.75%, 23.18%, 37.89%, and 25.90% compared to the control RPC sample without glass fibre.
- Furthermore, the addition of the glass fibre tends to enhance the flexural strength of RPC by 10.37%, 24.37%, 33.99%, and 26.65%, respectively, compared to control samples.
- The optimum glass fibre increases the load-carrying capacity, ductility, and energy absorption capacity of the RPC samples compared to the control RPC sample.
- When exposing the RPC samples to an acid attack, the compressive strength losses are noted as 0.44%, 1.61%, and 2.46% at 28, 56, and 90 days, respectively. Similarly, the weight losses are 2.18%, 3.42%, and 4.68% at 28, 56, and 90 days, respectively. The compressive strength and weight losses are compared under normal and acid immersion conditions.
- In summary, the SEM and EDAX analyses reveal that the optimum mix concrete (GF0.75) has a more compact and uniform microstructure with better elemental distribution compared to the conventional concrete (GF0). These improvements contribute to the enhanced mechanical properties of the RPC, making it a superior material for construction applications.
- The present study examines the mechanical, durability, and microstructural properties of the RPC subjected to steam curing conditions.

This study will be extended to various curing conditions, such as hot and normal water curing conditions. Additionally, the RPC samples can be investigated using various fibres. Furthermore, the studies could integrate advanced machine learning techniques to forecast RPC behaviour under various conditions to explore a new direction. This would help determine the best mix ratios and exposure scenarios, thereby increasing the precision of performance assessments. Moreover, real-time monitoring technologies, such as sensors and imaging tools, could offer valuable insights into microstructural transformations over time.

5. ACKNOWLEDGMENTS

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