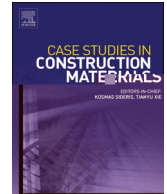




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Investigating the synergistic effects of carbon fiber and silica fume on concrete strength and eco-efficiency

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ABSTRACT

The present study endeavors to quantitatively evaluate the performance of concrete by incorporating carbon fiber reinforcement and micro silica addition. A comprehensive experimental investigation is conducted to examine the effects of these two additives on the concrete properties. Additionally, an eco-efficiency analysis is performed to assess the environmental impact of the modified concrete. Furthermore, a response surface optimization technique is employed to optimize the concrete mix design based on desired performance criteria. The findings of this study provide valuable insights into enhancing the performance and eco-efficiency of concrete by utilizing carbon fiber reinforcement and micro silica addition. To accomplish this objective, varying percentages of CF (ranging from 0% to 0.80%) and different densities of micro silica (ranging from 0 kg/m³ to 50 kg/m³) were incorporated into the concrete mixtures. Subsequent tests were conducted to evaluate the mechanical properties, including compressive strength, split tensile strength, and flexural strength, at least 3 specimens for each mix were tested. Furthermore, the eco-strength efficiency of the concrete mixtures was assessed by determining the ratios of embodied carbon. The results demonstrate that the inclusion of 0.60% CF and 26.5 kg/m³ of micro silica in the concrete mixture yields the optimal proportion, leading to a significant enhancement in compressive strength (CS), split tensile strength (STS), and flexural strength (FS) by 54.11%, 80%, and 36.6%, respectively, compared to a control sample devoid of CF and micro silica. Through thorough experimentation, a response surface methodology (RSM) was employed to develop an optimized model. Consequently, the derived equations enable the calculation of the impact of adding carbon fiber to concrete.

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1. Introduction

Concrete, globally favored for its affordability and high compressive strength, is primarily made with cement, which has negative environmental impacts. To promote sustainable construction, various materials are being used as replacements for cement. A variety of materials are currently used for cement replacement in sustainable construction [1–3], including fly ash, bottom ash, wood ash, meta-kaolin, palm oil fuel ash, Ground Granulated Blast-furnace Slag (GGBS), volcanic pumice powder ash, Rice husk, Sugarcane bagasse ash, coir fiber ash, and silica fume, among others [4]. These materials can be used as cement replacements and positively affect concrete's mechanical properties. One of the promising materials used as cement replacement material (CRM) is silica fume. Incorporating silica fume, an extremely pozzolanic byproduct of the ferrosilicon industry, can strengthen and increase the durability of concrete [5,6]. The study conducted by Shijun Zhao et al. [7] has recommended that producing high-performance concrete with excellent mechanical qualities may be accomplished by using SF as a replacement for modest volumes of cement in the mix. When silica fume is added to concrete, dynamic tensile loading produces improved results in terms of the material's mechanical characteristics and performance.

Extensive research has been conducted on silica fumes due to their remarkable physical and mechanical characteristics. The results have demonstrated a significant improvement in the dynamic tensile strength of samples, particularly when subjected to higher strain rates. The investigation carried out by Salim Barbhuiya et al. [8] found that 15% replacement of silica fume with cement has a positive impact on the mechanical properties of concrete. In one more prior research [9], it was determined that 10% SF is the optimal amount to be used as a cementitious material, with a compressive strength of approximately 32.5 N/mm² and a fracturing tensile strength of 3.45 N/mm²; further addition of silica fume results in a decrease in strength. There have been advancements in the production of concrete, resulting in the creation of new varieties with enhanced properties and remarkable usability. In addition to conventional constituents, these concrete also contain novel and innovative substances [10].

Various considerations, including mix proportions, water-to-cement ratios, chemical and mineral admixtures, and additional constituents, have been incorporated into contemporary concrete practices, alongside other significant aspects. Despite its impressive compressive strength, concrete is acknowledged for its insufficient tensile strength. It is crucial to address possible failures proactively in order to avert unexpected structural failures resulting from the inherent low tensile strength of concrete when subjected to continuous loading conditions. Various types of fibers, including synthetic, glass, steel, and natural fibers, are utilized in concrete [11]. The properties of fiber-reinforced concrete are subject to alteration based on the type of concrete used, the fibers' materials, shapes, arrangements, orientations, and densities [12]. The substance known as carbon fiber (CF) has an exceptionally high tensile strength [13,14]. It has been discovered that incorporating carbon fiber into concrete may increase the material's flexural strength and reduce the fracture width [15]. In civil engineering, carbon fibers are a popular material composed primarily of carbon atoms. The accumulation of carbon fibers in concrete can augment its durability against fatigue and impact, provided that the right amount is used. The low density and high thermal conductivity of carbon fibers have captured the interest of engineers [16]. Utilizing carbon fibers can aid in mitigating drying shrinkage issues and reducing fissure breadth [17]. Carbon fiber reinforced concrete (CFRC) has gained popularity in various fields due to its exceptional thermal conductivity with low weight and superior modulus of elasticity [18,19]. Numerous academic studies have been carried out in order to investigate the effect that carbon fibre has on concrete. These studies have shown that carbon fibre has the ability to improve the fracture resistance, ductility, and post-cracking behavior of concrete [20]. An examination into the effects of including carbon fibres in several proportions has been carried out, and the findings suggest that adding carbon fibres in an adequate amount may improve the durability of concrete while without affecting its compressive strength [21]. Furthermore, the utilisation of carbon fiber-reinforced concrete has shown potential in reducing maintenance costs and extending the operational lifespan of constructions [22]. This makes it an appealing option for a wide variety of applications, ranging from bridge decks to industrial flooring systems, which makes it a compelling choice for a lot of different uses. In the recent studies by Muhammad et al. [14], research findings indicate that incorporating CF into concrete can significantly enhance its mechanical characteristics and that adding 0.60% CF is the optimal amount that can be used in concrete. It increases compressive strength (CS) by 20.93% and split tensile strength (STS) by 59%. A study by Andrey et al. [23] has concluded that When preparing concrete, it is recommended to incorporate 0.2% by weight of carbon fibers into the cement. This will yield the finest outcomes. This technique has the potential to increase the CS (compressive strength) of concrete by 43.4% and the tensile strength (STS) by 17.5% while maintaining a high level of mechanical stabilization (2.8%).

Silica fume is a notable reactive pozzolans that has gained recognition for its potential to enhance the mechanical properties and long-lasting nature of concrete [24]. Silica fume is an auxiliary product that is generated from the production operations of silicon and ferrosilicon alloy [25]. The addition of silica fume to concrete mixtures causes it to go through a reaction with calcium hydroxide, which is a byproduct of the hydration process that cement goes through. As a consequence of this reaction, an additional gel composed of calcium silicate hydrate (C-S-H) is produced. Because of the improvements to the microstructure, the compressive strength is increased, the permeability is lowered, and the material's resistance to chemical attack and the alkali-silica reaction (ASR) is improved [26]. There has been a significant amount of investigation on the effectiveness of using silica fume as a partial replacement for cement in concrete [27,28]. These studies have repeatedly proved the good influence that silica fume has on the strength and durability of concrete, particularly in situations where the concrete is exposed to tough environmental circumstances, such as coastal projects and transportation infrastructure [29]. One example of such a scenario is when the concrete is subjected to a scenario where the concrete is subjected to harsh environmental conditions [30].

The originality of our study resides in the thorough evaluation of carbon fibre and silica fume as important concrete mixture additions. While earlier research has examined the distinct impacts of carbon fibre or silica fume on the characteristics of concrete, our study takes a ground-breaking tack by concurrently altering the amounts of both elements. Using this innovative method, we may

explore a variety of proportions and how they interact to affect the mechanical and structural qualities of concrete. Furthermore, by incorporating cutting-edge analytical methodologies and experimental procedures tailored to this unique mix, our work transcends the traditional limitations of concrete research. In order to better understand the intricate interactions between carbon fibre, silica fume, and the cementitious matrix, cutting-edge analytical methods and computer models are used. Our study has practical implications for the building sector in addition to the scientific advancements. The results of our investigation might completely alter how concrete buildings are designed and function. We hope that our work will result in more resilient and long-lasting building materials that provide advantages such better load-bearing capacity, improved fracture resistance, and longer durability.

To optimize the mechanical properties of concrete, a combination of carbon fibers and micro silica is being investigated. Series of mechanical tests were conducted to investigate the combine effects of carbon fiber and silica fume on CS, STS, and FS, for investigating each characteristic 3 samples were prepared for each proportion. Additionally, RSM statistical model was developed for each response and equation were generated to predict the mechanical strength of concrete containing carbon fiber and silica fume, and also determined the optimal proportions of carbon fibers and micro silica for use in the construction industry.

1.1. Design of experiments

1.1.1. Background

Design of Experiments (DOE) is a methodology that encompasses the consideration of numerous input variables in order to achieve comprehensive analysis. [31]. This technique can increase the efficacy of experiments, and numerous industrial sectors utilize it for this purpose [32]. Empirical research on some aspect of a system, procedure, or product is the focus of a specialized subfield of applied statistics. This line of inquiry centers on modifying the values of the input variables to examine how these modifications influence the measured variables. The scope of DOE extends to both real-world physical processes and computer-generated simulation models [33]. Historically, the OVAT method was utilized to solve problems involving multiple parameters. This method entailed holding all variables constant except for one and conducting experiments until the optimal result was attained for the examined factor. Each variable is subjected to the procedure until the correct solution is found, considering all the problem's variables. The procedure requires extensive data sets and multiple trials, which can be expensive, time-consuming, and labor-intensive despite its precision and simplicity.

To assess the efficiency of concrete, numerous aspects must be taken into account. However, by thoroughly contemplating and paying meticulous attention to detail, we can attain remarkable outcomes [34]. The DoE technique facilitates the comprehension of arithmetical modeling by exposing the influence of each constituent on the dependent variable. Consequently, the quantity of data that must be collected to get correct findings is reduced. Academics who put in the effort to develop their topic knowledge and problem-solving abilities will find that the variety of analyses offered by the Design of experiment (DoE) presents a stimulating and gratifying challenge [35]. It is encouraging to note that DoE has emerged as a prominent approach in recent years to research various construction materials. The comprehensive utilization of DoE in concrete research is a positive development. The process starts with forecasting the strength of concrete and extends to creating various design combinations. The integration of numerical equations can enhance the effectiveness of nondestructive testing (NDT) for accurately evaluating the strength of conventional concrete [11–21].

The preferred method for situations like this involves utilizing the SLR, a simple linear regression technique in conjunction with a scatter plot. New methods of assessment, such as the Response Surface Method, may now be used to produce forecasts that are both precise and highly specific [36]. DoE processes are particularly helpful for identifying the possibility of material substitution, and a substantial fraction of the most recent publications use a more complex way of interpreting test findings [37]. Several potential substitute materials, such as tire rubber [38], fly ash [39], and others, have been put through various DoE testing protocols to determine their effectiveness. Further research has been conducted to enhance concrete design procedures using response surface methodology [40], curve fitting techniques [41], and ANNs-based approaches.

1.1.2. Response surface technique

Response surface methodology (RSM) is a widely recognized experimental design approach that enables researchers to methodically investigate the impacts and interdependencies of multiple factors related to response variables. The employed research methodology in this study bears resemblance to the Taguchi technique, aiming primarily to streamline the testing process in order to attain optimal results. According to Bradley et al. [42], To select the response site that yields the best results, the RSM method necessitates a study of the response surface's shape. In this study, both the positive maximum (+1) and the negative minimum (−1) are considered, as well as the trajectory of the ridges. The RSM model is excellent because it takes into account the combined effect of a large number of variables and then generates an optimal design for the response variable. Thus, the RSM paradigm is highly effective. The RSM method is an excellent instrument for reducing the time and money spent on research and the number of laboratory tests required. Using a numerical method allows us to solve problems in a manner that is both more efficient and effective [43]. In addition to this, it analyzes how the different components communicate with one another to enhance the model's accuracy and reliability. The observed data displays a quadratic pattern, indicating the potential for incomplete representation of certain curved systems. Nonetheless, this presents an opportunity to investigate and learn more about the world.

Even though RSM does not inherently define the method of data collection, it provides a comprehensive analysis instrument for results and discoveries. Excitingly, numerous research approaches are currently being utilized. Among these are the Box-Behnken design (BBD), the three-level (3 k) complete factorial Design, the central composite Design (CCD), and the Doehlert design matrix (DM), among others.

This study employed the Response Surface Methodology (RSM) as its primary research approach. The RSM involved various

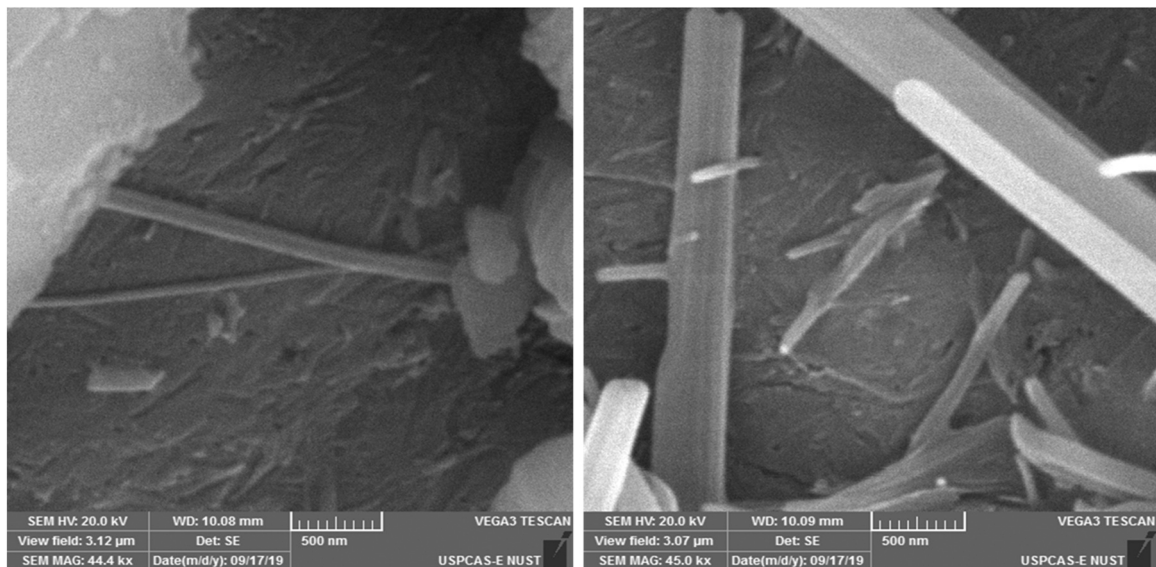


Fig. 1. FESEM of carbon fiber.

components, including experimental designs, mathematical modeling, mix proportioning, and optimization. Design Expert 13 software was utilized to facilitate the optimization process. The study emphasizes investigating the impact of carbon fiber and micro silica on the characteristics of hardened concrete. Both carbon fiber (CF) and micro silica are used as separate variables in the research. The process enables a comprehensive understanding of the subject matter.

2. Materials and mix proportions

2.1. Materials

Ordinary Portland cement Type I (OPC) was employed in this research study, adhering to the standards outlined in ASTM C150M-15 for the binder material utilized. Carbon fibers, an essential constituent of concrete, were procured from local vendors. The material properties were evaluated using the existing equipment available in our laboratory, following the standard parameters provided by the carbon fiber supplier. This assessment aimed to determine the suitability of carbon fibers for concrete production and other testing procedures. By closely monitoring the incorporation of carbon fibers in concrete and maximizing the interaction between the fibers and the concrete matrix, it is possible to enhance the strength of concrete beyond its inherent capabilities.

Precautionary measures were implemented to ensure the appropriate utilization of carbon fibers in concrete manufacturing. Subsequent testing demonstrated that the industrial grade 36 carbon fiber exhibited all the typical properties associated with carbon fibers. A research investigation was conducted to verify the accuracy of the test results. The research findings indicate that the optimal length of carbon fiber strands should not exceed 10 millimeters. Moreover, incorporating fibers into various concrete elements enhances their durability and evaluation methods. These conclusions were derived from the analysis of concrete samples and their performance under different conditions. The collected data serve as evidence of the research findings. The emphasis on maintaining the length of carbon fiber strands within 10 millimeters aims to highlight their effectiveness in enhancing the properties of the material. The micro silica used in this investigation was obtained from a local supplier. The substance was then transported, and its density and other properties were determined. There is a correlation between its properties and reduced water absorption and its ability to be incorporated into materials with specific particulate sizes or dimensions. The coarse aggregate was obtained from a close-by supplier. A granular aggregate that was easily accessible in the region was employed in the study. The procurement of a superplasticizer having a density of 1200 kg per m³ from local sources was conducted during the manufacture of concrete. The principal objective of this procurement was to fulfill the water requirements. Research has been conducted to analyze the chemical composition of carbon fiber and superplasticizers to detect potentially hazardous substances that could compromise the fiber's strength. FESEM of carbon fiber can be seen in Fig. 1.

2.2. Mix proportioning using RSM

The research was conducted on the production of controlled concrete, following the ACI 211.1–91 guidelines, without the inclusion of carbon fiber. The software Design Expert 13 was utilized to conduct a mixed design incorporating different carbon fiber proportions using response surface methodology. Manipulating the independent variables of carbon fiber and micro silica is a key aspect of RSM, as it directly impacts the dependent variables and their outcomes. Utilizing the optimal design feature of the Design Expert 13 software,

Table 1
RSM Proportioning.

MIX	Binder Kg/m ³	CF (%)	Micro silica Kg/m ³	C.A Kg/m ³	F.A Kg/m ³	Water Kg/m ³	SP (%)
CF0%MS0	503.5	0.00%	0	890	740	195	1
CF0%MS26.5	503.5	0.00%	26.5	890	740	195	1
CF0.60%MS26.5	503.5	0.60%	26.5	890	740	195	1
CF0.20%MS24	503.5	0.20%	24	890	740	195	1
CF0.40%MS24	503.5	0.40%	24	890	740	195	1
CF0.60%MS24	503.5	0.60%	24	890	740	195	1
CF0.80%MS24	503.5	0.80%	24	890	740	195	1
CF0%MS50	503.5	0%	50	890	740	195	1
CF0.20%MS50	503.5	0.20%	50	890	740	195	1
CF0.40%MS50	503.5	0.40%	50	890	740	195	1
CF0.60%MS50	503.5	0.60%	50	890	740	195	1
CF0.80%MS50	503.5	0.80%	50	890	740	195	1



Fig. 2. (a) SEM of carbon fiber, (b) cured samples, (c) compressive strength testing (d) split tensile strength testing.

the percentage of the mixture was successfully calculated. CF from 0% to 0.80% and micro silica with varying density from 0 kg/m³ to 50 kg/m³ was added in the variability of mixes. The concrete investigation evaluates its mechanical properties, including CS, STS, and FS. Additionally, EC and ESE are considered for the environmental evaluation of concrete. All other materials, including super-plasticizers, fine aggregate, coarse aggregate, and water, were held constant. RSM produced a variety of mixtures with differing proportions and densities of CF and micro silica, respectively. The [Table 1](#) depicts the proportioning performed by RSM. [Table 3](#) shows

Table 2
Codes followed for mechanical testing.

Mechanical Test	Codes followed
Compressive strength	ASTM C78/C78M
Split tensile strength	ASTMC496
Flexural strength	ASTM C78/C78M-21

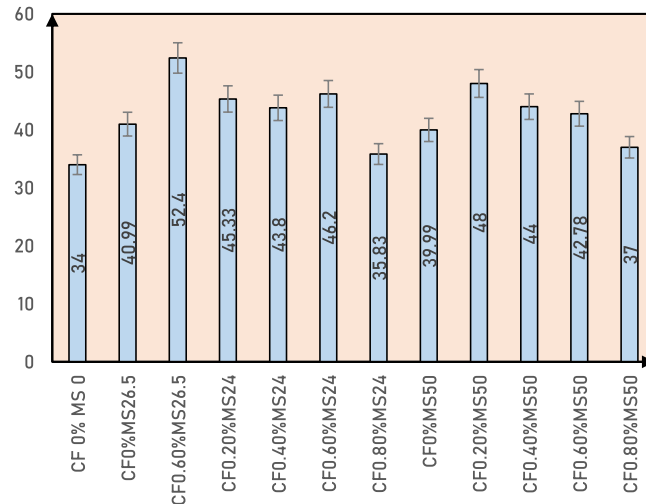


Fig. 3. Compressive Strength.

the input and output data in RSM (Fig. 2).

2.3. Preparation of specimen

The dry ingredients, such as cement and aggregates, were mixed for two minutes before adding water and superplasticizer. The incorporation of the mixture into the concrete was carried out meticulously for a few minutes. During the preparation of the concrete, a gradual distribution of carbon fiber was observed on its surface. Following the proper integration of the concrete, specimens were subsequently cast for further analysis. To determine the compressive strength, rectangular blocks measuring $100 \times 100 \times 100 \text{ mm}^3$ were cast following the guidelines outlined in ASTM C78/C78M. Tensile strength samples were cast following ASTM C496 specifications, featuring 200 mm in height and a diameter of 100 mm. Following the ASTM C78/C78M-21 standard, the specimen was prepared for flexural strength testing, and all samples were evaluated on the 28th day after casting. Codes and specifications followed for testing can be seen in Table 2.

3. Results and discussion

3.1. Mechanical properties

3.1.1. Compressive strength

Fig. 1 illustrates the compressive strength of each concrete mix. The research findings demonstrate that the control mix, which contains 0% carbon fiber and micro silica, exhibits a strength of 34 MPa. Introducing micro silica at a dosage of approximately 26.5 kg/m^3 in the CF 0%MS 26.5 mix results in a concrete strength increase of approximately 20.55% compared to the control mix. Conversely, when 0.20% of carbon fiber is combined with 24 kg/m^3 of micro silica, the concrete strength is enhanced by 33.32% relative to the control mix. The CF 0.20%, MS 50 mix demonstrates a strength of approximately 48 MPa, representing a 41.17% improvement over the control mix. If the amount of fiber increased to 0.40% with the same quantity of micro-silica 50 kg/m^3 in CF 0.40% MS 50, strength increases by 29.41% which shows that an increase in the fiber content from 0.20% to 0.40% with the same amount of micro silica 50 kg/m^3 resulted in the reduction of strength. As the amount of carbon fiber raised to 0.60% with micro silica of 50 kg/m^3 in the mix, CF 0.60% MS50 compressive strength increased by 25.82%, but if the quantity of silica decreased to 26.5 kg/m^3 with the same 0.60% of CF the CS upsurges by 54.11% which is the maximum CS among the mixes. The prior studies by Muhammad Khan et al. [14] found that concrete containing 0.60% of carbon fiber increases compressive strength by 20.93%. According to the previous investigation, the quantity of CF which gives the optimum results is 0.60% [44]. Silica also plays a vital role in enhancing the concrete's compressive strength; concrete containing 26.5 kg/m^3 silica with 0.60% of CF gives the optimum results. It was found that

Factor Coding: Actual

CS

● Design Points

35.83 52.4

X1 = A

X2 = B

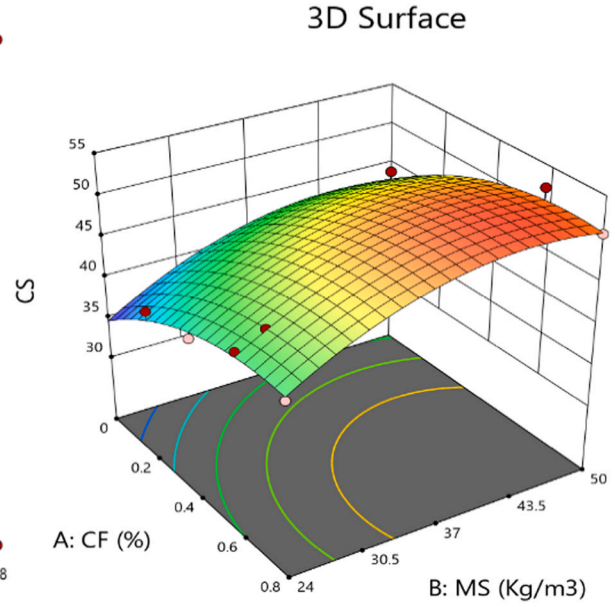
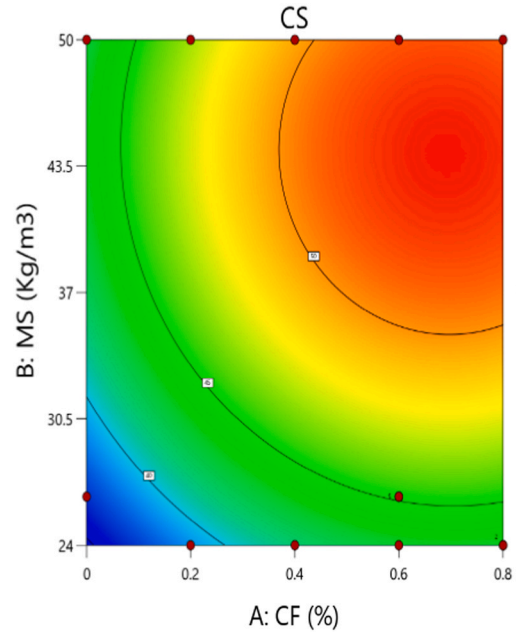


Fig. 4. 2D contour plot (left) and 3D response surface diagram (right).

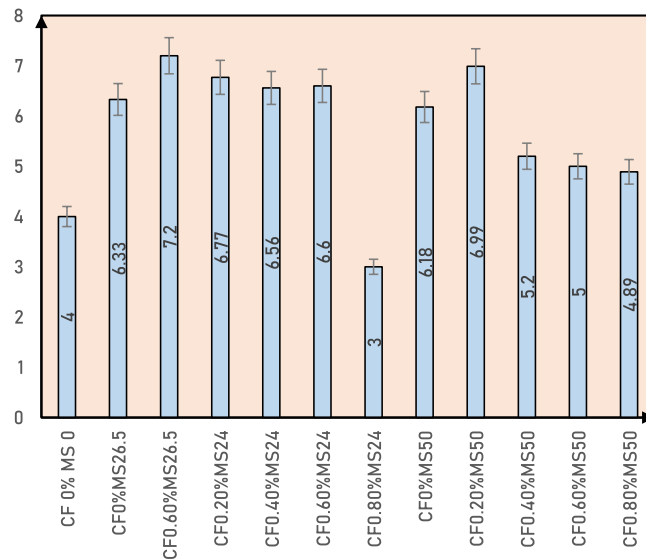


Fig. 5. Split Tensile Strength.

0.60% of CF in concrete has maximum strength and further addition of CF reduces its strength it is because the excessive amount of CF results in agglomeration, the process of agglomeration has the ability to produce localized zones that are distinguished by a noticeably increased concentration of fibres, which, in turn, causes a disruption in the uniform dispersion of fibres throughout the concrete mixture. As a consequence of this, these agglomerations of fibres have the ability to operate as stress concentrators, so weakening the integrity of the nearby matrix and lowering the total toughness [14]. The observed synergistic effects in these samples provide evidence that the incorporation of CF and SF in different quantities might result in improved concrete characteristics. The synergistic effects are particularly evident when achieving an ideal equilibrium between the two materials, leading to enhanced compressive strength.

The CS was evaluated using the response surface technique, which involved the generation of 2D plot and 3D response surface. These 2D and 3D response surface shows that CS of concrete increases with addition of micro silica and research suggests that incorporating 0.60% of CF and 26.5 kg/m^3 of micro silica, can result in achieving the optimal strength.

3.1.2. Split tensile strength

The split tensile strength (STS) test results are presented in Fig. 3. The control mix demonstrates an STS of approximately 3 MPa. It is evident that the STS increases with a higher percentage of carbon fiber (CF) and silica. The results indicate that incorporating 0% CF and 26.5 kg/m^3 of silica in the concrete leads to a 58.25% increase in STS. Furthermore, when the CF content is 0.20% and the silica dosage remains at 24 kg/m^3 , the STS improves by 69.25%. Similarly, by keeping the silica dosage constant at 24 kg/m^3 and increasing the CF content to 0.40%, the STS rises by 64%. As the CF percentage increases to 0.6% with the same silica quantity, STS increases by 65% compared to the control mix. Increasing the CF up to 0.80% with the same 24 kg/m^3 in the concrete mix shows a decline in the STS, and CS decreases by 25% compared to the control sample. If the quantity of silica increases to 50 kg/m^3 with 0% CF gives the STS of about 6.99 MPa, about 54.5% more than the control sample, which shows that micro silica also has a positive influence on the STS of concrete. The 0.20% of CF added with 50 kg/m^3 gives the STS 74% more than the control sample. If the percentage of CF kept increasing to 0.40% with the same amount of micro silica strength starts declining, which is 30% more than the control sample. 0.60% of CF also results in the decline of STS, having an STS of about 5 MPa, which is about 25% more than the control sample. If CF is 0.80% with 50 kg/m^3 , the STS increases by 22.25%. The optimum results can be found using 0.60% of CF with 26.25 kg/m^3 , which is about 7.2 MPa more than any other mix. CF are a kind of material that has excellent strength capabilities and has the capability to bridge and reinforce these cracks in an effective manner. The incorporation of CF into concrete serves the purpose of distributing tensile stresses throughout the material, which prevents fractures from spreading further. Because of this, there has been a noticeable improvement in the material's resistance to cracking, as well as an increase in the tensile strength of the material [14]. According to the prior study, concrete containing 0.60% of CF gives the optimum results for STS [14]. The strength of concrete begins to decline if the quantity of CF increases more than 0.60% because of the development of voids due to the fiber agglomerates, which is the reason for the reduction of strength [16].

Fig. 4 illustrates the polynomial correlation between concrete's CS and STS. It demonstrates a strong relationship among the CS and STS of concrete. R^2 is a statistical measure that specifies how thoroughly the data fitting the regression line. Value of R^2 is between 0 and 1, and a value close to 1 designates that the model is more effective. Fig. 4 depicts an equation where "X" represents compressive strength and "Y" represents divided tensile strength.

By means of the response surface technique 2D plot of contour and response surface 3D model was generated for STS of concrete. These both 2D and 3D response surface shows that STS of concrete increases with addition of silica fume and optimum strength can be

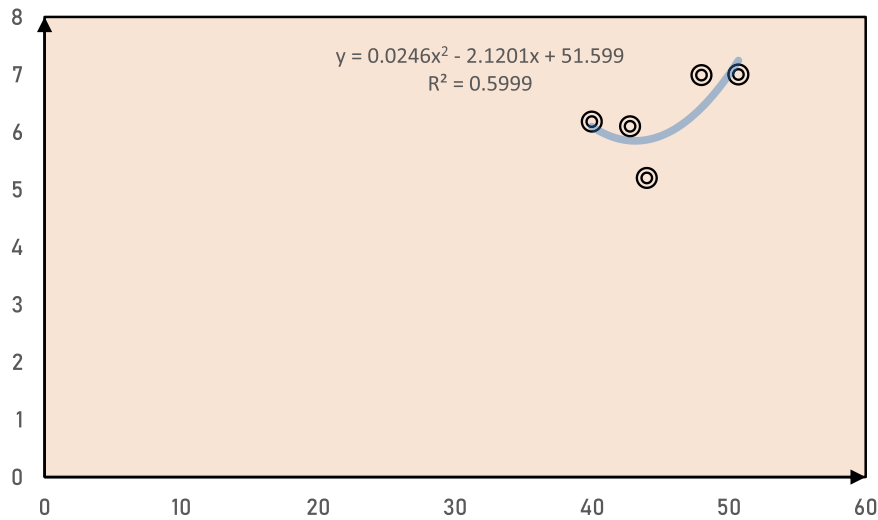


Fig. 6. relationship between compressive and tensile strength.

obtained by using 0.60% of CF and 26.5 kg/m³ of silica nano-silica (Fig. 5).

3.1.3. Flexural strength

Fig. 6 presents the flexural strength (FS) of 28-day-old concrete. It is evident that the control sample, which does not contain carbon fiber (CF) and micro silica, exhibits the lowest flexural strength compared to other compositions. The FS of the control sample measures 3.38 MPa. In contrast to the control sample, the addition of CF and micro silica enhances the flexural strength. The inclusion of 0.20% CF and 24 kg/m³ of micro silica increases the flexural strength by 27%. It can be seen that increasing the CF to 0.40% with the same quantity of micro silica increases the sample's strength by 28%. If the fraction of CF increases to 0.60 percent with 24 kg/m³ of micro silica, flexural strength increases by 28.52%. While adding more than 0.60% CF has a negative consequence on the FS of concrete, there is only a 13% increase in flexural strength compared to the control sample. According to the CF is 0% and 50 kg/m³, flexural strength increases by 19.8%, demonstrating that the accumulation of micro silica to concrete positively impacts the resilience of concrete. With the same quantity of micro silica, adding 0.20%, CF increases the sample's strength by 30% to 4.42 MPa. As the amount of CF increased to 0.40% with 50 kg/m³ of micro silica 25.5%, the flexural strength of concrete decreased, while adding 0.80% with the same quantity of micro silica had no effect. Adding 0.60 percent CF to 26.5 kg/m³ of micro silica produces the maximum flexural strength of all the mixtures, which is 36.62% higher than the control mix. CF is used in order to strengthen the structural integrity of the concrete matrix. As a result of this, the concrete matrix is better able to withstand greater loads and displays enhanced resistance to deformation when it is exposed to bending stresses. This is particularly beneficial in circumstances in which structural components, such beams and slabs, are subjected to flexural forces [14]. In an earlier study conducted by Petruka et al. [45], adding 3% CF improved the FS of concrete by 26.75%. In their investigation, Bashir et al. [46] found that 10% silica fume with 5% of carbon fiber gives flexural strength increased by 48.17%.

Fig. 7 illustrates the 2D contour and response surface 3D model for concrete's FS. The 2D contour diagram and 3D response surface model plainly demonstrate that FS depends on both CF and micro silica. It increases as micro silica and CF levels rise.

3.2. Assessment of sustainability

3.2.1. Embodied carbon (EC)

Table 3. Embodied carbon of all the mixes was found using the carbon factor taken from the available literature for the assessment of the sustainability of each mix. The Table 4 below represents the embodied carbon factor for each material used in concrete preparation.

Fig. 7 shows that the control mix contains the least quantity of modified carbon, 463.0932 kgCO₂.m³, compared to the other mixtures. The amount of CF directly correlates with the amount of embodied carbon; as CF increases, so does the amount of embodied carbon. The maximum embodied carbon in the blend containing 0.80% CF and 50 kg/m³ of micro silica is approximately 597.21 kgCO₂.m³, 28.96% higher than the control mix. If the quantity of CF remains unchanged at 0.80%, but the amount of micro silica is reduced to 24 kg/m³, the amount of embodied carbon increases by 28.8%. If CF is decreased to 0.60% and micro silica is 26.5 kg/m³, embodied carbon will increase by 21.66%. According to a previous study [37], raising the amount of CF in concrete increases the EC (embodied carbon). Other characteristics of concrete, such as CS and STS, and longevity, among others, must also be considered before a proportion can be deemed suitable or advantageous. For this reason, it is crucial to evaluate the ESE of concrete to find the most appropriate and advantageous mixture.

2D contour plot and 3D response surface was generated using RSM. It can be seen in the 2D contour and 3D model that embodied

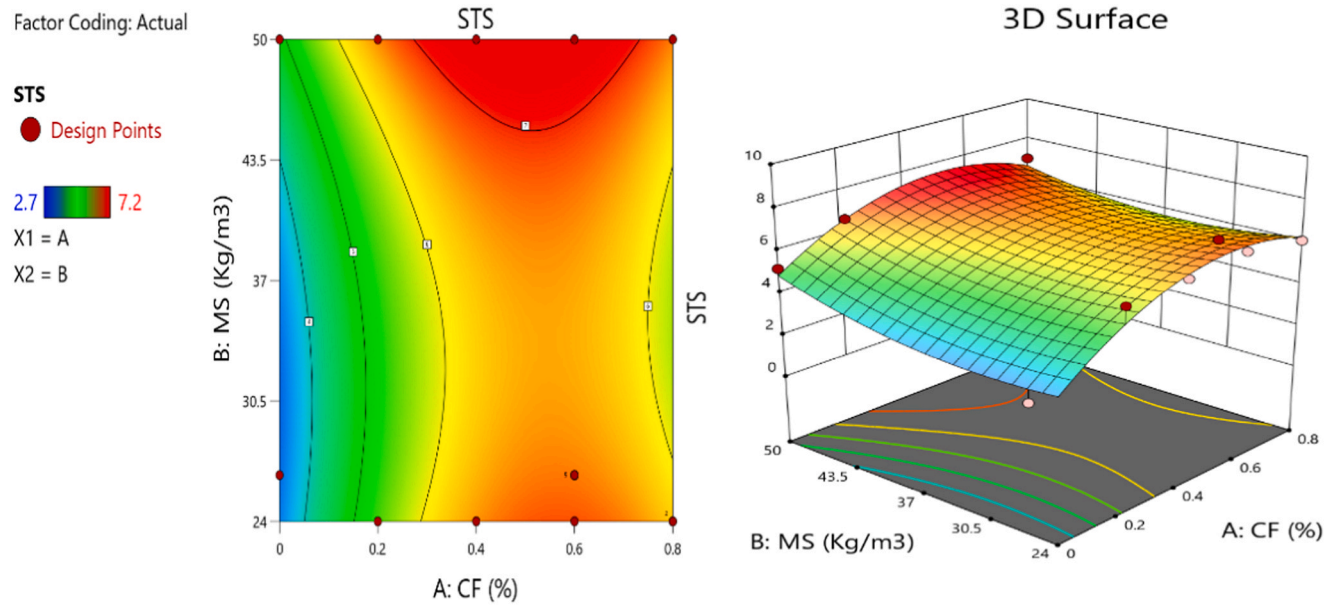


Fig. 7. 2D contour (left) & 3D response surface diagram for STS.

Table 3
Input and out responses in RSM.

S.NO	Carbon Fiber (%)	Silica Fume (Kg/m ³)	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (Mpa)	Embodied Carbon	Eco Strength Efficiency
1	0.4	24	43.8	6.56	4.33	530.13	0.0773
2	0.6	50	42.78	5	4.18	563.98	0.0929
3	0.6	26.5	52.4	7.2	4.61	563.42	0.08047
4	0.6	24	46.2	6.6	4.34	563.362	0.0777
5	0.6	26.5	52.4	7.2	4.61	563.42	0.08047
6	0.6	26.5	52.4	7.2	4.61	563.42	0.08047
7	0.6	26.5	52.4	7.2	4.61	563.42	0.08047
8	0.6	26.5	52.4	7.2	4.61	563.42	0.08047
9	0.2	50	48	6.99	4.42	497.52	0.09285
10	0	26.5	40.99	6.33	4.09	463.72	0.0773
11	0.2	24	45.33	6.77	4.30	496.9	0.0804
12	0.8	24	35.83	3	3.84	596.59	0.0717
13	0.4	50	44	5.2	4.24	530.75	0.0904
14	0	50	39.99	6.18	4.05	464.29	0.0947
15	0.8	24	35.83	3	3.84	596.59	0.0717
16	0.8	50	37	4.89	4	597.21	0.0848

Table 4
EC (Embodied carbon) factors.

Material	Embodied Carbon Factor CO ₂ (Kg/Kg)	References
OPC	0.82	[47]
Silica fume	0.024	[48]
Carbon Fiber	33	[49]
Fine Aggregate	0.0139	[50]
Super Plasticizer	0.72	[51]
Coarse Aggregate	3.4	[49]
Water	0	[52]

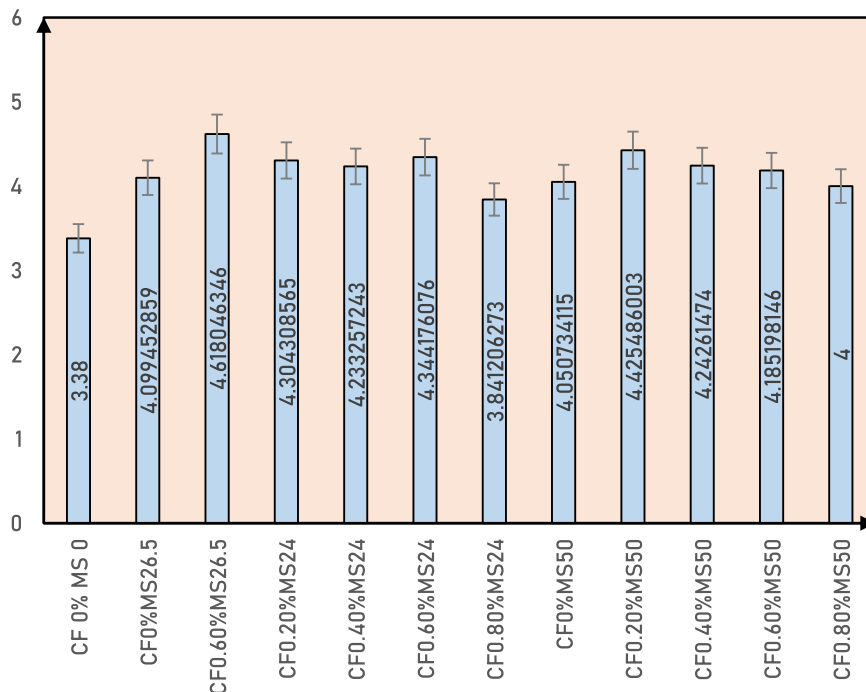


Fig. 8. Flexural Strength.

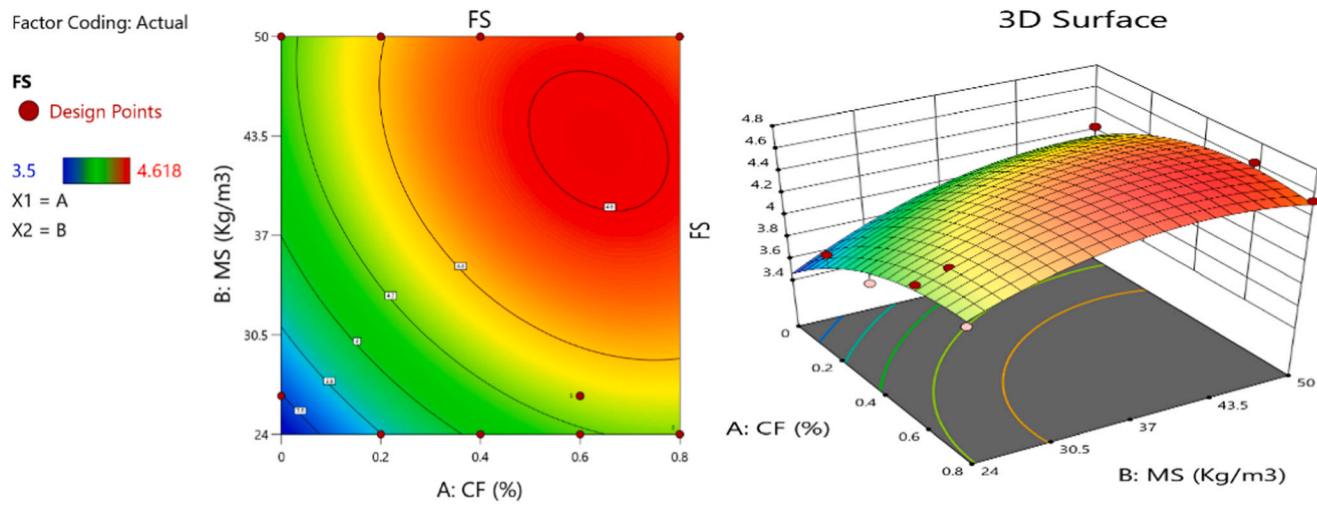


Fig. 9. 2D contour (left) & 3D response surface model (right) of Flexural Strength.

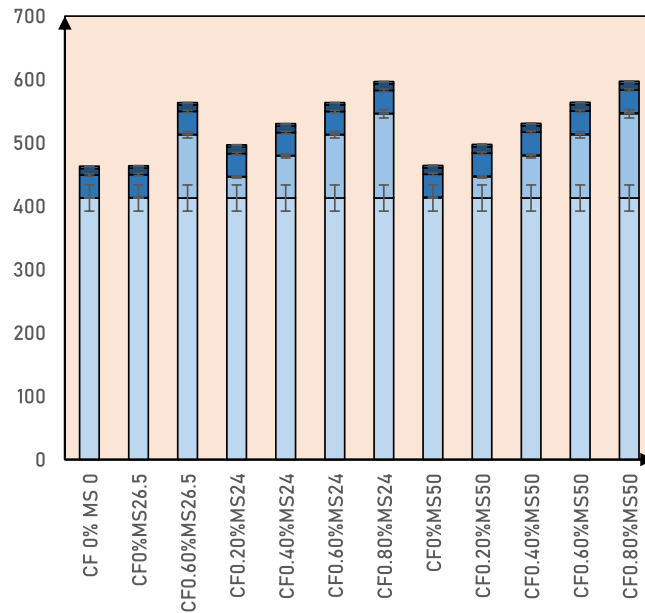


Fig. 10. Embodied Carbon.

carbon of each mix depend on the percentage of CF used in the proportion because of its high carbon factor mixture having high amount of carbon has more embodied carbon.

3.2.2. Eco-strength efficiency (ESE)

The equation shown below, denoted as Eq. 1, is utilized to calculate the eco-strength efficiency of each concrete mix:

$$\text{Eco-strength efficiency} = \frac{\text{28th day compressive strength}}{\text{total embodied carbon of ECC}} \quad (1)$$

Fig. 8 depicts the ESE of each mixture; it reveals that the ESE of the control mixture is approximately 0.73419 MPa/kgCO₂.m³. As 0.20% of CF and 24 kg/m³ of micro silica are added, Eco strength efficiency increases by 9.65% compared to the control sample; 0.40% of CF and the same amount of micro silica are added, Eco strength efficiency increases by 5.31%. When CF is 0.60%, and 24 kg/m³ of micro silica is present, the eco-strength efficacy increases by 5.89%. As the amount of micro silica raises to 50 kg/m³, the eco-strength also increases. Eco-strength efficiency is 29% greater in the mix CF0%MS50 CF is 0% with 50 kg/m³ than in the control sample; as the quantity of CF in the mix increases, eco-strength efficiency begins to decline. Adding 0.20% CF to 50 kg/m³ increases eco-strength efficiency by 20.9%; increasing CF to 0.40% increases eco-strength efficiency by 23.17% compared to the control sample. It was discovered that CF0%MS50 has the maximum eco-strength efficiency value among all mixtures. The observed synergistic effects in these samples illustrate that the incorporation of CF and SF in different quantities might result in improved concrete characteristics. The synergistic effects are particularly evident when there is a harmonious equilibrium achieved between the two materials, leading to enhanced sustainability. The use of supplementary cementitious materials (SCMs), such as silica fume (SF), plays a crucial role in enhancing the overall synergistic benefits of eco-efficient concrete mixes. SF effectively reduces the embodied carbon content, hence contributing significantly to the sustainability and environmental performance of concrete. The results of this study emphasize the need of customizing the proportions of CF and SF to meet the individual requirements of a project in order to optimise both performance and sustainability (Fig. 9).

RSM generated 2D contour and 3D response surface model in the Fig. 10. shows that Eco strength efficiency depend on both micro silica and CF. As the micro silica increases in the mix Eco strength efficiency also increases.

4. Analysis of variance using RSM

The model was constructed using the response surface methodology, incorporating five responses: compressive strength (CS), split tensile strength (STS), flexural strength (FS), embodied carbon (EC), and eco-strength efficiency (ESE). Eqs. 3–6 represent the mathematical expressions used to model these responses. Among the various models considered, the quadratic model was found to provide the best fit for all the responses, as evident from the contour plots and 3D response surface models presented at the top. A significance threshold of 5% was deemed acceptable to validate each evaluated model, ensuring a 95% confidence interval [53,54]. Table 2 provides a summary of the analysis of variance for the response surface methodology. Because a 5% significance criterion was applied to each response, any number less than 0.05 was considered noteworthy in the field of study. All models with a high F-value and a P-value less than 0.05 are considered to have statistically significant outcomes. It can be seen in Table 5 that each response has a

Table 5
ANOVA Summary.

Responses	Source	Sum of Squares	df	Mean Square	F-value	p-value	Significance
Compressive Strength	Model	223.52	5	44.70	44.18	< 0.0001	significant
	A-CF	101.82	1	101.82	100.63	< 0.0001	
	B-MS	138.92	1	138.92	137.30	< 0.0001	
	AB	0.1307	1	0.1307	0.1292	0.7268	
	A ²	17.22	1	17.22	17.02	0.0021	
	B ²	4.32	1	4.32	4.27	0.0657	
	Residual	10.12	10	1.01			
	Lack of Fit	10.12	5	2.02			
	Pure Error	0.0000	5	0.0000			
Split-Tensile Strength	Model	15.55	5	3.11	17.73	0.0001	significant
	A-CF	7.90	1	7.90	45.02	< 0.0001	
	B-MS	1.85	1	1.85	10.57	0.0087	
	AB	0.3977	1	0.3977	2.27	0.1630	
	A ²	6.40	1	6.40	36.48	0.0001	
	B ²	0.1623	1	0.1623	0.9256	0.3587	
	Residual	1.75	10	0.1754			
	Lack of Fit	1.75	5	0.3507			
	Pure Error	0.0000	5	0.0000			
Flexural Strength	Model	0.9713	5	0.1943	30.24	< 0.0001	significant
	A-CF	0.4753	1	0.4753	73.99	< 0.0001	
	B-MS	0.5423	1	0.5423	84.41	< 0.0001	
	AB	0.0551	1	0.0551	8.58	0.0151	
	A ²	0.0860	1	0.0860	13.38	0.0044	
	B ²	0.0136	1	0.0136	2.11	0.1770	
	Residual	0.0642	10	0.0064			
	Lack of Fit	0.0642	5	0.0128			
	Pure Error	0.0000	5	0.0000			
Embodied Carbon	Model	28555.29	5	5711.06	2.652E+09	< 0.0001	significant
	A-CF	26416.82	1	26416.82	1.226E+10	< 0.0001	
	B-MS	0.8575	1	0.8575	3.981E+05	< 0.0001	
	AB	0.0000	1	0.0000	7.94	0.0182	
	A ²	0.0000	1	0.0000	11.11	0.0076	
	B ²	7.028E-06	1	7.028E-06	3.26	0.1010	
	Residual	0.0000	10	2.154E-06			
	Lack of Fit	0.0000	5	4.308E-06			
	Pure Error	0.0000	5	0.0000			
Eco-strength Efficiency	Model	0.0007	5	0.0001	41.99	< 0.0001	significant
	A-CF	0.0000	1	0.0000	11.87	0.0063	
	B-MS	0.0005	1	0.0005	140.14	< 0.0001	
	AB	7.940E-06	1	7.940E-06	2.28	0.1618	
	A ²	0.0000	1	0.0000	14.15	0.0037	
	B ²	0.0000	1	0.0000	3.39	0.0953	
	Residual	0.0000	10	3.478E-06			
	Lack of Fit	0.0000	5	6.957E-06			
	Pure Error	0.0000	5	0.0000			

Table 6
Parameter for validation of models.

Model Validation Constraints	CS	STS	FS	EC	ESE
Std. Dev.	1.01	0.4188	0.0801	0.0015	0.0019
Mean	44.63	6.30	4.23	544.88	0.0821
C.V.%	2.25	6.65	1.90	0.0003	2.27
PRESS	46.63	13.53	0.3747	0.0002	0.0002
-2 Log Likelihood	38.07	10.03	-42.88	-170.89	-163.22
R-Squared	0.9567	0.8986	0.9380	0.9999	0.9545
Adj R-Squared	0.9350	0.8480	0.9069	0.9999	0.9381
Pred R-Squared	0.8004	0.2180	0.6381	0.9999	0.7768
Adeq Precision	23.1462	16.1675	19.9730	1.485E+05	18.9820
BIC	54.71	26.67	-26.24	-154.25	-146.58
AICc	59.41	31.37	-21.54	-149.55	-141.88

high F-value, and the P-value of every model is less than or equal to 0.0001, which shows that model of each response is significant. F-values for CS, STS, FS, EC, and ESE models are 44.18, 17.73, 30.24, 2.652E+09, and 41.99, respectively, which indicates that each model is statistically noteworthy. Based on the observed F-value, it is estimated that there is a 0.01% probability of a noise level generating such a large F-value. When the p-values are below 0.05, it indicates that the model terms hold statistical significance. In

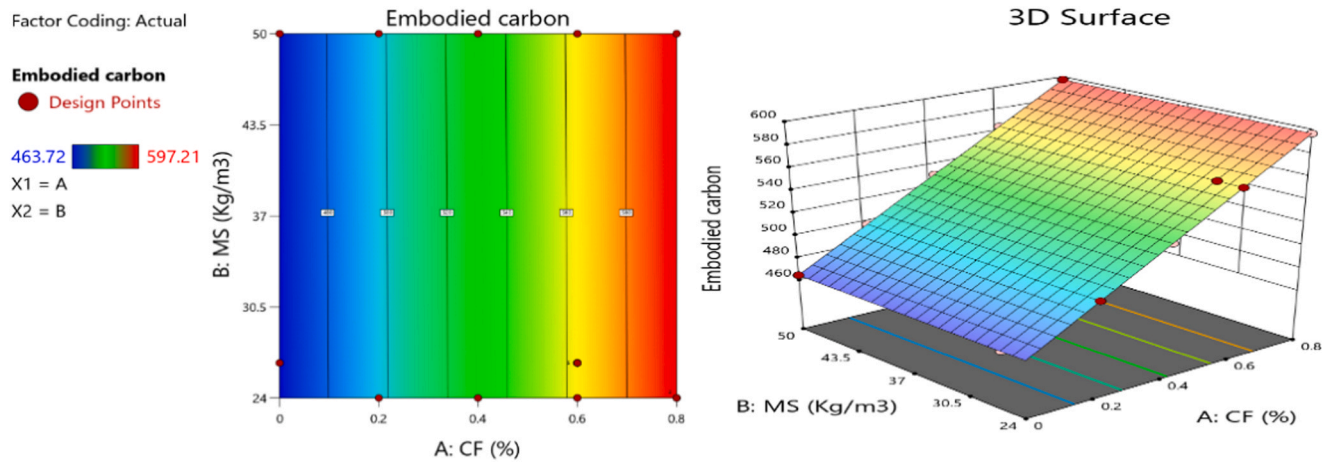


Fig. 11. 2D contour (left) & 3D response surface model (right) of Embodied carbon.

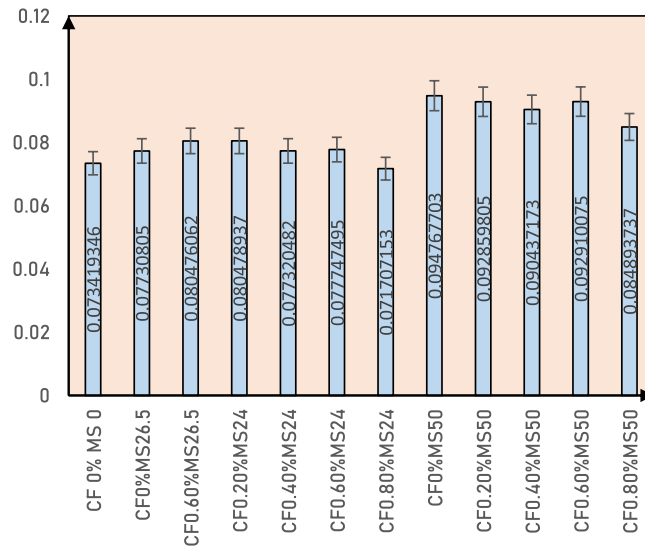


Fig. 12. Eco-strength Efficiency.

response to compressive strength (CS), the significance of model terms A, B, and A² cannot be overstated. For the case of Split tensile strength (STS), significant model terms are A, B, and A². Flexural strength (FS) has the significant model terms A, B, AB, and A². While significant model terms of Embodied carbon (EC) are A, B, AB, A² and for Eco strength efficiency (ESE), A, B, and A² are noteworthy model terms.

RSM generated all these equations. Using the equation expressed in coded factors enables the generation of forecasts regarding the response by utilizing established levels of every component. The default setting assigns a value of +1 to high levels of the components and a value of -1 to low levels. Using coded equations is a valuable tool for evaluating various elements' significance concerning factor coefficients during comparative analysis. A represents the CF, and B represents the micro silica. Input variable CF is in %, while micro silica is in kg/m³.

$$CS = 49.2116 + 4.12617*A + 3.9526*B - 0.156829*AB - 2.79255*A^2 - 3.50793*B^2 \quad (2)$$

$$STS = 6.31268 + 1.14905*A + 0.45652*B - 0.273553*AB - 1.7023*A^2 + 0.679946*B^2 \quad (3)$$

$$FS = 4.48059 + 0.281907*A + 0.246947*B - 0.10183*AB - 0.197337*A^2 - 0.196469*B^2 \quad (4)$$

$$EC = 530.437 + 66.4619*A + 0.310541*B - 0.00179387*AB - 0.00329245*A^2 + 0.00447424*B^2 \quad (5)$$

$$ESE = 0.091885 - 0.00262727*A + 0.00740401*B - 0.00122231*AB - 0.00472172*A^2 - 0.00579814*B^2 \quad (6)$$

The validation parameter for each model is presented in Table 6. The coefficient of determination (R²) is employed as an indicator to assess the predictive performance of the model [55,56]. Ranging between 0 and 1, a value close to 1 indicates a well-predicted model [53,57]. In this study, the developed models exhibit high R² values close to 1. The R² values for CS, STS, FS, EC, and ESE are 0.9567, 0.8986, 0.9380, 0.9999, and 0.9545, respectively. These R² values indicate a high level of accuracy in the prediction of the models. Also, the best-predicted model variance among the adjusted R² and forecasted R² should be below 0.2. According to the developed model, the variance among forecasted and adjusted R² for each response is below 0.2. Additionally, the acceptable precision must be greater than 4. Adequate precision for each response exceeds four. The precise values for CS, STS, FS, EC, and ESE are 23,1462; 16,1675; 19,9730; 1,485E+05; and 18,9820, respectively. It shows that all the responses have a high degree of accuracy (Figs. 11, 12).

Normal residuals and plots of expected values versus actual values are two of the most important diagnostic graphics. The response surface serves as the beginning point for constructing these graphs. Two model plot types are shown below in Figs. 13–16. To be considered the best model, the data point must correspond to a possible high degree of fitted line in predicted vs. actual plots. The data points are close to the fitted line in each of the five responses. Figs. 13–16 provides a visual depiction of normal plots of residuals for your perusal. It demonstrates that the nodes on the diagonal line are linear, supporting the theory that error factors have been evenly distributed. This is because it illustrates the linearity of the horizontal line. This fundamental characteristic must be present in any model that purports to be accurate. This is because if the residuals are assumed to have a normal distribution, then 95% of them should fall within the range of -2 to +2, presuming they have a normal distribution. If we regard them to have a normal distribution, then the residuals should also have a normal distribution [58]. It can be seen that all residual plots are consistent with this, which is evidence that the models can make accurate predictions (Table 7).

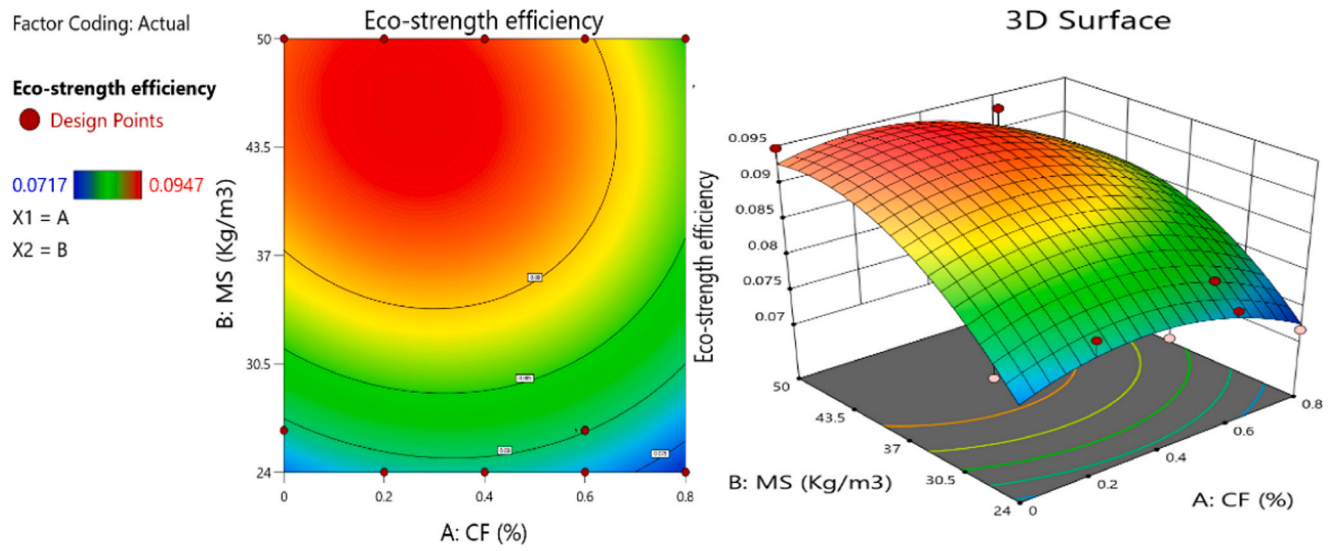


Fig. 13. 2D contour (left) & 3D response surface model (right) of Eco Strength Efficiency.

CS

Color points by value of STS:
2.7 7.2

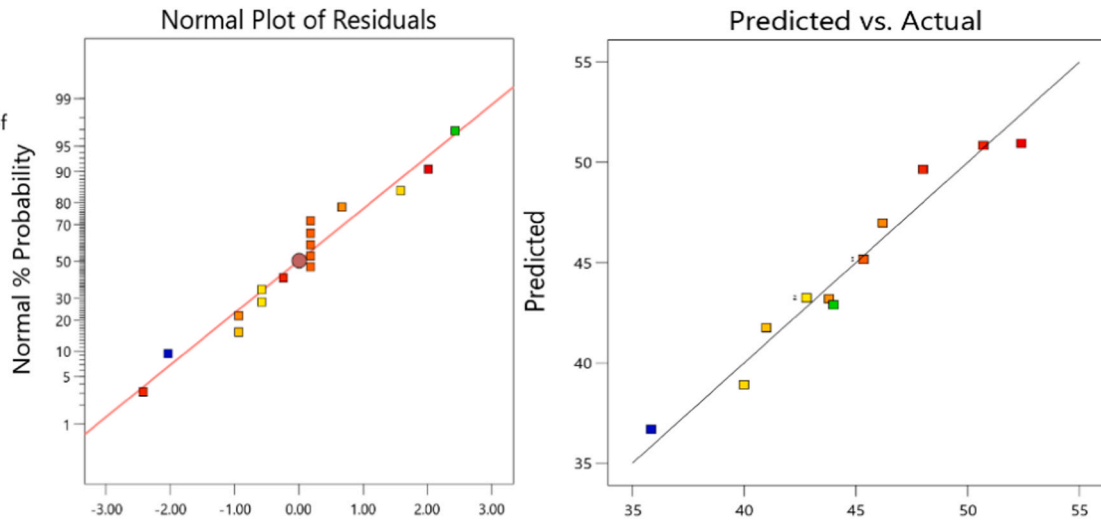


Fig. 14. Normal residuals plot (left) & Predicted versus Actual plot for CS.

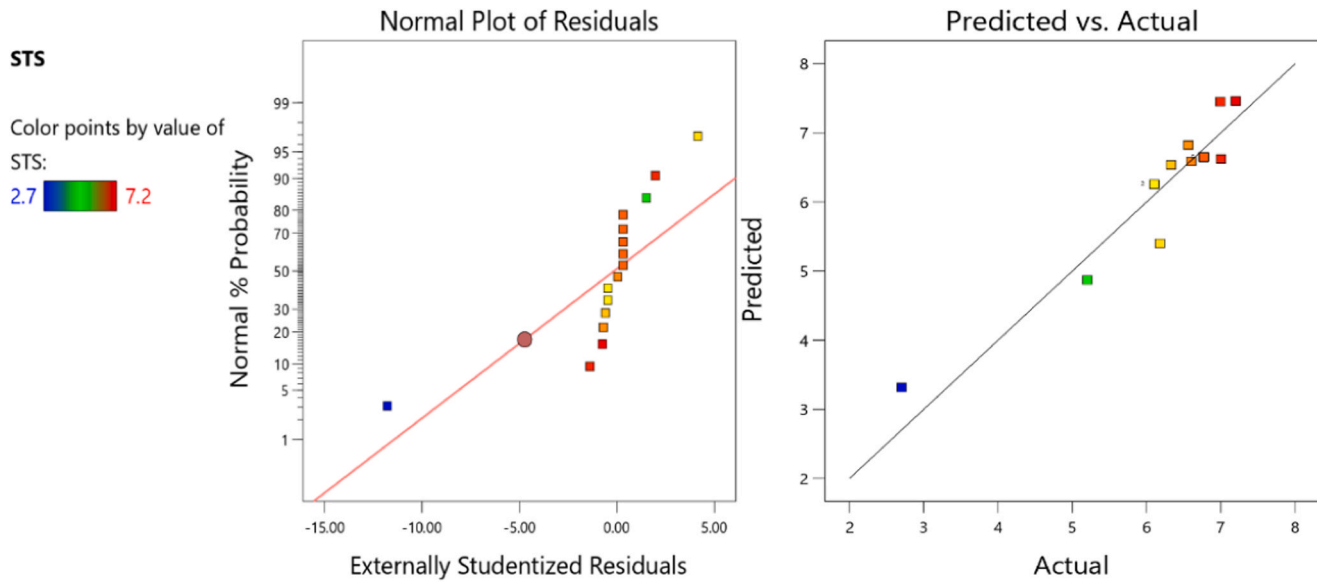


Fig. 15. Normal residuals plot (left) & Predicted versus Actual plot for STS.

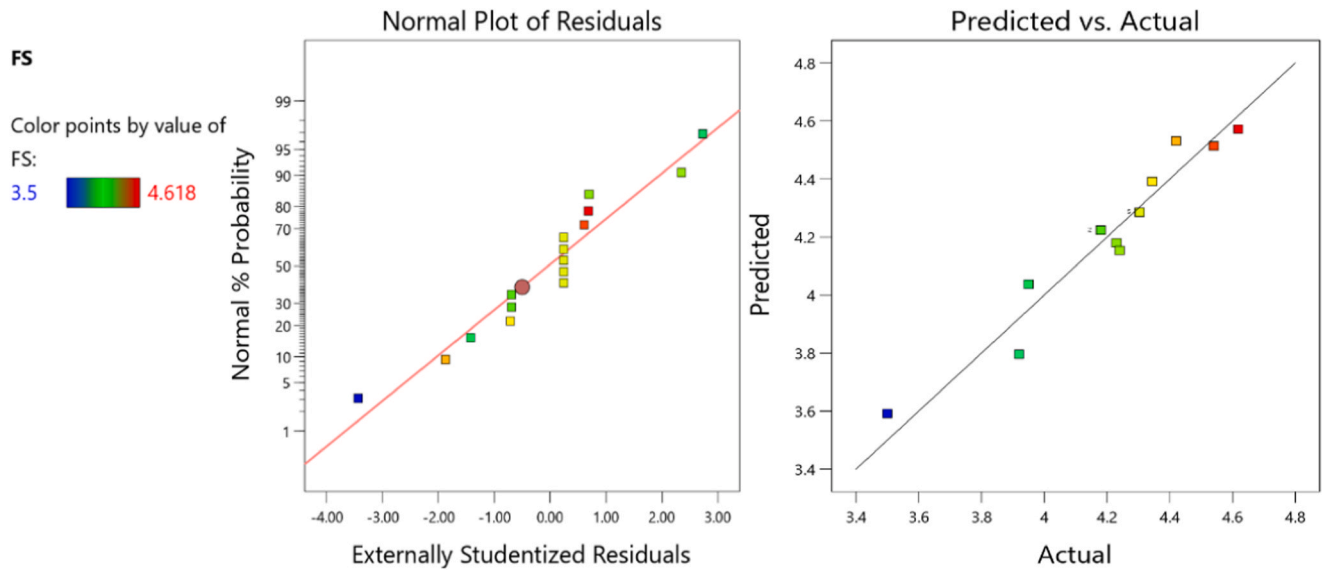


Fig. 16. Normal residuals plot (left) & Predicted versus Actual plot for FS.

Table 7
Optimization of input variables.

Factors	Variable (Input Factors)		Response (output Factors)						
	Carbon Fiber	Nano-Silica (kg/m ³)	Compressive strength	Split tensile strength	Flexural Strength	Embodied Carbon	Eco-Strength Efficiency		
Value	Minimum	0%	24	35.83	2.7	3.5	463.72	0.0717	
	Maximum	0.8%	50	52.4	7.2	4.618	597.21	0.0947	
Goal	In range	In range	In range	In range	In range	In range	Maximize	Minimize	
Optimization results	0.8	24	43.2415	6.2564	4.22357	596.591	0.0725562		
Desirability	0.979								

5. Multi-objective optimization

The technique commonly referred to as multi-objective optimization has been devised to ascertain the input variable that holds the highest overall significance, thereby enabling the attainment of a larger number of responses simultaneously [28]. In numerous practical optimization scenarios, the identification of multiple optimal solutions becomes imperative, particularly when confronted with conflicting objectives. Consequently, it is essential to accord precedence to the adoption of this approach. The deployment of the model has been enhanced in terms of time and resource efficiency through the implementation of optimization strategies targeting the independently controlled variable [59]. The attainment of a significant level remains one of the key objectives in this regard. The objective function may or may not be considered when determining the objectives of the variables during the optimization process. At any point in the described process, these objectives may be defined. Multi-response optimization was performed using both factors (CF and micro silica), considering all the output factors (CS, STS, FS, EC, and ESE) at 28 days. It can be seen in the table that CS, STS, and FS optimization goal is set to be in range while the optimization goal of EC is set to maximize, and ESE is set to minimize the optimization goal. The optimization results show that optimized results can be obtained by using 0.8% of CF and 24 kg/m³ of micro silica, and gives the optimized results for CS, STS, FS, EC, and ESE are 43.24 MPa, 6.256 MPa, 4.223 MPa, 596.591 kgCO₂.m³, 0.07255 MPa/kgCO₂.m³ respectively. As per this model's optimization, the model's desirability is above 97.9%. This shows that this model has highly desirable results (Figs. 17–20).

6. Model validation

The experimental results were used to validate the optimization results to verify the optimized proportions. CF was set at 0.8%, and micro silica at 24 kg/m² based on the optimum optimization procedure results. The alteration among experimental and predicted values is expressed as a percentage, indicating that the difference is less than five percent. Indicating that the model is extremely accurate. Table 8 shows the model validation.

7. Conclusions

The primary aim of this investigation was to evaluate the mechanical properties of concrete enhanced with carbon fiber and micro silica. The present work offers significant contributions to the understanding of the combined impacts of CF and SF on concrete mixes, hence providing vital insights. Our study has specifically shown that the incorporation of CF and SF may result in substantial improvements in compressive, split tensile, and flexural strengths. This discovery enhances our comprehension of the synergistic effects of these components on enhancing the performance of concrete. Various proportions were established using a statistical design of experiments technique called Response Surface Methodology (RSM). Statistical models were developed to predict the desired characteristics of the concrete by determining the optimal amounts of key components. These models successfully forecasted the properties of the concrete. The influence of carbon fiber (CF) and micro silica on each response was analyzed using Analysis of Variance (ANOVA). The findings demonstrate a multifaceted, nonlinear correlation among the aforementioned factors. The study revealed that there was a correlation between the amount of carbon fibre and silica fume used and a reduction in concrete strength. However, it should be noted that the pace of this loss varied across the different proportions that were evaluated. The results indicate that the rate of concrete strength degradation is affected by complex interactions among the constituent materials, as well as other factors like conditions for curing and the surrounding environment. The key findings of this study are as follows:

- The main objective of the research was to develop response surface models and perform multi-objective optimization. The input variables for the response surface models were carbon fiber (CF) ranging from 0% to 0.80% and micro silica ranging from 0 to kg/m³.
- Based on the interaction among all the input variables (A: Carbon fiber; B: micro silica), it was determined that the quadratic model provided the optimal fit for all the output variables, including CS, STS, FS, EC, and ESE.
- The coefficient of determination (R-Squared) values for each of the responses, including CS, STS, FS, EC, and ESE, are 0.9567, 0.8986, 0.9380, 0.9999, and 0.9545, respectively.

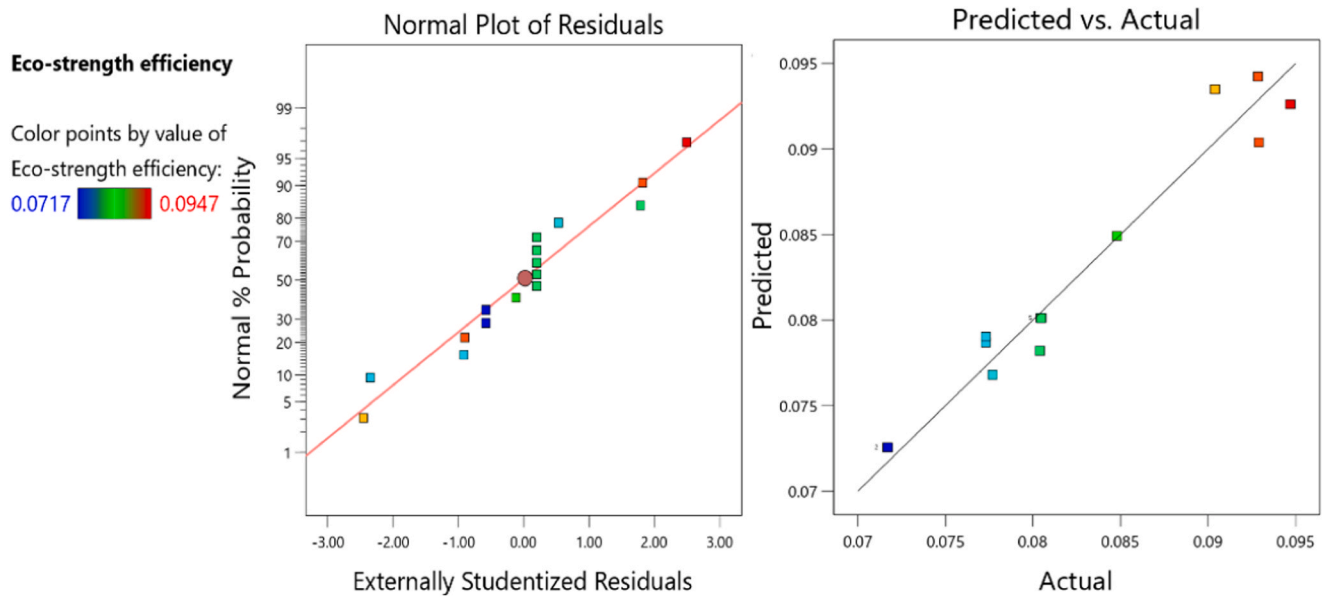


Fig. 17. Normal residuals plot (left) & Predicted versus Actual plot (right) for ESE.

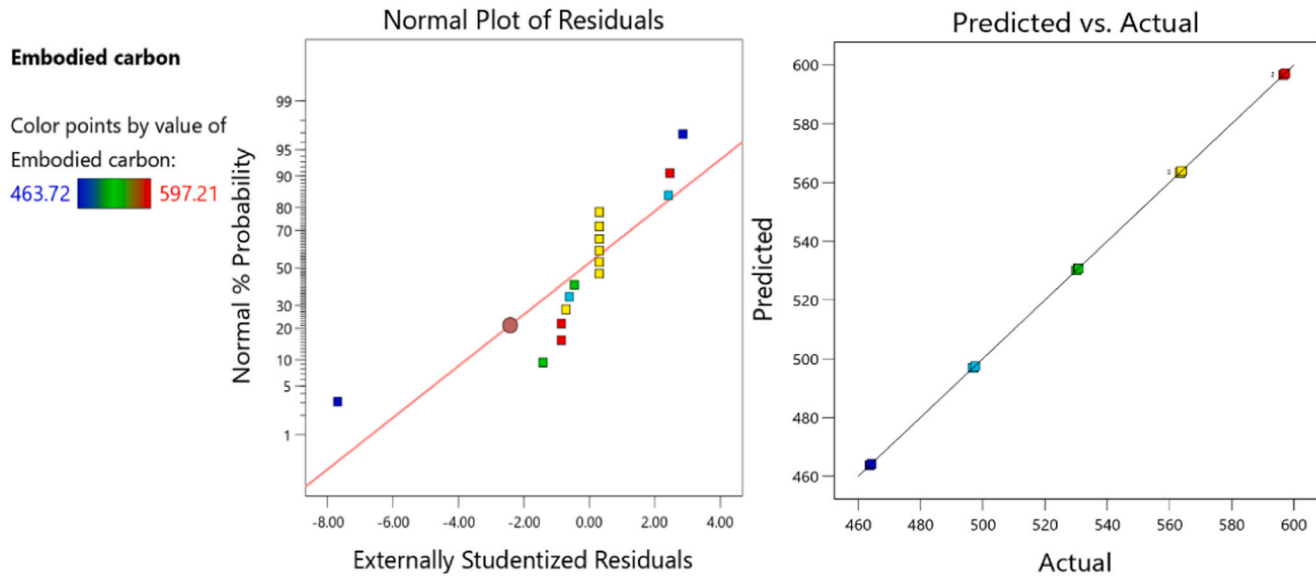


Fig. 18. Normal residuals plot (left) & Predicted versus Actual plot for EC.

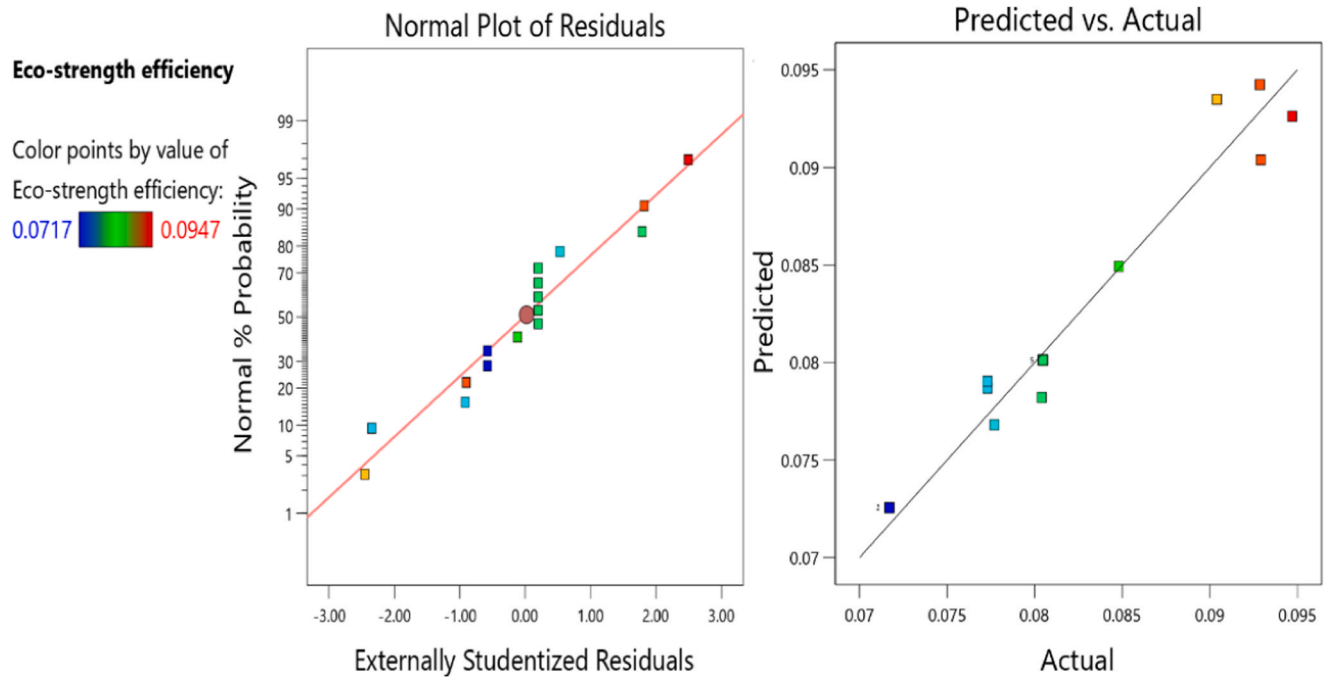


Fig. 19. Normal residuals plot (left) & Predicted versus Actual plot (right) for ESE.

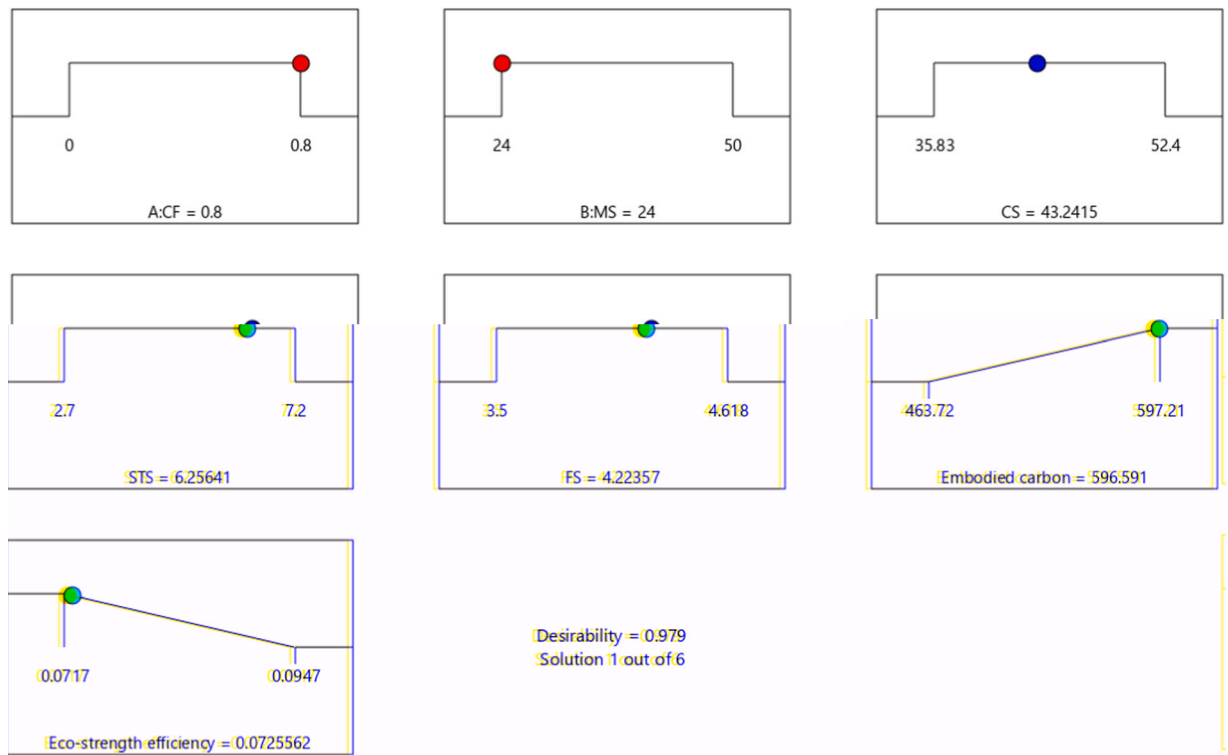


Fig. 20. Ramp Diagram (optimized results).

Table 8

Validation of model.

Response	Predicted	Experimental	Error (%)
Compressive strength	43.2415	44.5	2.91%
Split-Tensile strength	6.2564	6.4	2.29%
Flexural strength	4.22357	4.4	4.17%

- The incorporation of 0.60% carbon fiber and 26.5 kg/m³ of micro silica resulted in optimal CS, STS, and FS, which were approximately 54.11%, 80%, and 36.6% higher than the control sample, respectively.
- Through the optimization process, all the responses were optimized. The optimized responses included CS, STS, FS, EC, and ESE values of 43.2415, 6.2564, 4.22357, 596.591, and 0.0725562, respectively, with a desirability of 97.9%.
- The use of two-dimensional contour diagrams and three-dimensional response surface diagrams effectively depicted the impact of variations in the components and their interrelationships on the observed responses. Three-dimensional response diagram indicates that increasing the CF concentration above 0.60% leads to a reduction in the effectiveness of the concrete. The attainment of optimal outcomes is facilitated by the incorporation of 26.5 kg/m³ of SF and 0.60% of the CF.
- Based on the analysis of a two-dimensional contour map, it can be shown that the incorporation of higher levels of CF and increased quantities of SF contribute to a notable escalation in the embodied carbon. The inclusion of CF and SF is directly associated with the embodied carbon of concrete.

8. Limitations

It is crucial to recognize and appreciate the constraints and restrictions inherent in this particular investigation. The study is subject to some limitations, such as the restricted sample size and geographical coverage, which may impact the extent to which our findings may be applied to wider populations. Furthermore, despite our diligent attempts to reduce possible biases, the intricate nature of concrete behavior when subjected to different ratios of carbon fibre and silica fume poses significant obstacles that need additional exploration. It is highly recommended that future research endeavors should build upon our study and effectively address the aforementioned constraints. By doing so, our knowledge of sustainable building materials may be significantly advanced.

9. Future recommendations

Based on the findings of this inquiry, it has been determined that the optimal percentage of CF and optimum utilization of micro silica in concrete to enhance its mechanical and environmental characteristics is at a percentage of 0.60% and a quantity of 25.5 kg/m³. Further research is recommended to ascertain more precise proportions of carbon fiber and micro silica in order to develop concrete that is both environmentally sustainable and highly durable. Additionally, forthcoming studies should prioritize the examination of other properties of carbon fiber and micro silica blended concrete, such as its resistance to environmental factors and acid attacks, as well as its overall durability. Furthermore, investigations can be conducted to identify the most cost-effective methods of producing carbon fiber and micro silica-infused concrete. It is crucial to continue exploring the use of carbon fiber and micro silica in concrete, and actively promote its adoption within the construction industry. It is recommended that future research endeavors or practical implementations give due attention to the potential for conducting comprehensive cost analyses. The assessments should include several factors, including the procurement of materials, the processing of such materials, their transportation, and the labor required. Additionally, it is important to assess the possible long-term cost savings resulting from enhanced concrete performance. The aforementioned parameters play a crucial role in assessing the cost-effectiveness of CF-SF mixes in specific construction projects, while also ensuring that the compositions are in line with the project's specific goals and constraints.

CRedit authorship contribution statement

Dodo Yakubu: Methodology, Software. **Cazacu Christiana Emilia:** Formal analysis, Writing – review & editing. **Gălățanu Teofil:** Writing – review & editing, Visualization. **RADU Dorin:** Supervision, Software, Methodology. **Afzal Muhammad Talal:** Methodology, Investigation. **Khan Muhammad Basit:** Writing – original draft, Visualization, Validation, Software, Project administration. **Waqar Ahsan:** Methodology, Formal analysis, Conceptualization. **Almujibah Hamad R.:** Resources, Project administration. **Althoey Fadi:** Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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References

- [1] M. Glavind, 5 - Sustainability of cement, concrete and cement replacement materials in construction," in Woodhead Publishing Series in Civil and Structural Engineering, J. M. B. T.-S. of C. M. Khatib, Ed. Woodhead Publishing, 2009, pp. 120–147.
- [2] E. Isik, E. Harirchian, H. Bilgin, K. Jadhav, The effect of material strength and discontinuity in RC structures according to different site-specific design spectra, *Res. Eng. Struct. Mater.* vol. 7 (3) (2021) 413–430, <https://doi.org/10.17515/resm2021.273st0303>.
- [3] A. Bakis, E. Isik, A.A. El, M. Ülker, Mechanical properties of reactive powder concretes produced using pumice powder, *J. Wuhan. Univ. Technol. Sci. Ed.* vol. 34 (2) (2019) 353–360, <https://doi.org/10.1007/s11595-019-2059-1>.
- [4] M. Basit, E. Engineering, U.T. Petronas, B.S. Is-kandar, Production of biochar from waste biomass feedstock and its applications in sustainable, *Construction* vol. 19 (01) (2023).
- [5] D.K. Panesar, "3 - Supplementary cementing materials," in Woodhead Publishing Series in Civil and Structural Engineering, S. B. T.-D. in the F. and R. of C. (Second E. Mindess, Ed. Woodhead Publishing, 2019, pp. 55–85.
- [6] M. Chatbi, et al., Nano-clay platelet integration for enhanced bending performance of concrete beams resting on elastic foundation: an analytical investigation, *Materials* vol. 16 (14) (2023), <https://doi.org/10.3390/ma16145040>.
- [7] S. Zhao, Q. Zhang, Effect of silica fume in concrete on mechanical properties and dynamic behaviors under impact loading, *Materials (Basel, Switz.)* vol. 12 (19) (2019), <https://doi.org/10.3390/ma12193263>.
- [8] S.D.V. T. T. S, S. Yuvaraj "Investigation on the Strength and Durability Properties of Concrete with GGBS and Silica fume," no. July, pp. 1–52018, , 1–5..
- [9] M.A. Keerio, S.A. Abbasi, A. Kumar, N. Bheel "Effect of Silica Fume as Cementitious Material and Waste Glass as Fine Aggregate Replacement Constituent on Selected Properties of Concrete Effect of Silica Fume as Cementitious Material and Waste Glass as Fine Aggregate Replacement Constituent on Selecte," no. April 2023, 2022, doi: 10.1007/s12633-020-00806-62022.
- [10] M. Bustillo Revuelta, "Special Concrete BT - Construction Materials: Geology, Production and Applications," M. Bustillo Revuelta, Ed. Cham: Springer International Publishing, 2021, pp. 275–306.
- [11] D.W. Fowler, "7 - Repair materials for concrete structures," in Woodhead Publishing Series in Civil and Structural Engineering, N. B. T.-F. Delatte Distress and Repair of Concrete Structures, Ed. Woodhead Publishing, 2009, pp. 194–207.
- [12] F. Micelli, A. Renzi, A.G. Kandalaf, and S. Moro, "7 - Fiber-reinforced concrete and ultrahigh-performance fiber-reinforced concrete materials," P. Samui, D. Kim, N. R. Iyer, and S. B. T.-N. M. in C. E. Chaudhary, Eds. Butterworth-Heinemann, 2020, pp. 273–314.
- [13] M. Atiyeh, E. Aydin, Carbon-fiber enriched cement-based composites for better sustainability, *Materials (Basel, Switz.)* vol. 13 (8) (2020), <https://doi.org/10.3390/ma13081899>.
- [14] M.B. Khan, A. Waqar, 2023, Waqar, Carbon Fiber-Reinforced Concrete Composites Using Response," no. March, 2023, doi: 10.3390/buildings13040852.

- [15] D.D.L. Chung, Cement reinforced with short carbon fibers: a multifunctional material, *Compos. Part B Eng.* vol. 31 (6) (2000) 511–526, [https://doi.org/10.1016/S1359-8368\(99\)00071-2](https://doi.org/10.1016/S1359-8368(99)00071-2).
- [16] M. Yakhlaif, "Development of Carbon Fiber Reinforced Self-Consolidating Concrete Patch for Repair Applications," 2013.
- [17] Q. Li, Y. Li, Y. Zhang, Y. Han, Application of cement-based carbon fiber material in construction of building durability, *Int. J. Anal. Chem.*, Vol. 2022 (2022) 3562209, <https://doi.org/10.1155/2022/3562209>.
- [18] S.A. Mirdehghan, "1 - Fibrous polymeric composites," in *The Textile Institute Book Series*, M. B. T.-E. P. F. M. Latifi, Ed. Woodhead Publishing, 2021, pp. 1–58.
- [19] M.B. Khan, N. Shafiq, A. Waqar, D. Radu, C. Cismaş, M. Imran, Effects of Jute Fiber on Fresh and Hardened Characteristics of Concrete with Effects of Jute Fiber on Fresh and Hardened Characteristics of Concrete with Environmental Assessment," no. June, 2023, doi: 10.3390/buildings130716912023.
- [20] Q. Zheng, D.D.L. Chung, Carbon fiber reinforced cement composites improved by using chemical agents, *Cem. Concr. Res.* vol. 19 (1) (1989) 25–41, [https://doi.org/10.1016/0008-8846\(89\)90062-8](https://doi.org/10.1016/0008-8846(89)90062-8).
- [21] X. Xu, Application of carbon fiber cement-based composites in improving construction durability, *Int. J. Anal. Chem.* 2022 (2022) 2323534, <https://doi.org/10.1155/2022/2323534>.
- [22] A. Patchen, S. Young, D. Penumadu, An investigation of mechanical properties of recycled carbon fiber reinforced ultra-high-performance concrete, *Materials (Basel, Switz.)* vol. 16 (1) (2022), <https://doi.org/10.3390/ma16010314>.
- [23] A. Nevsky, K. Kudyakov, I. Danke, A. Kudyakov, and V. Kudyakov, Improvement of cement concrete strength properties by carbon fiber additives," *AIP Conf. Proc.*, vol. 1698, no. January 2016, 2016, doi: 10.1063/1.4937875.
- [24] M. Soomro, V.W.Y. Tam, and A.C. Jorge Evangelista, "3 - Industrial and agro-waste materials for use in recycled concrete," in *Woodhead Publishing Series in Civil and Structural Engineering*, V. W. Y. Tam, M. Soomro, and A. C. B. T.-R. C. Jorge Evangelista, Eds. Woodhead Publishing, 2023, pp. 47–117.
- [25] R. Siddique, N. Chahal, Use of silicon and ferrosilicon industry by-products (silica fume) in cement paste and mortar, *Resour. Conserv. Recycl.* vol. 55 (8) (2011) 739–744, <https://doi.org/10.1016/j.resconrec.2011.03.004>.
- [26] H.M. Khater, Effect of silica fume on the characterization of the geopolymer materials, *Int. J. Adv. Struct. Eng.* vol. 5 (1) (2013) 12, <https://doi.org/10.1186/2008-6695-5-12>.
- [27] S. Tak, P. Gupta, A. Kumar, A. Sofi, C. Mei Yun, Effect of using silica fume as a partial replacement of cement in concrete, *Mater. Today Proc.* (2023), <https://doi.org/10.1016/j.matpr.2023.04.205>.
- [28] M.B. Khan, et al., Enhancing the mechanical and environmental performance of engineered cementitious composite with metakaolin, silica fume, and graphene nanoplatelets, *Constr. Build. Mater.* vol. 404 (2023) 133187, <https://doi.org/10.1016/j.conbuildmat.2023.133187>.
- [29] M.H. Mizan, K. Matsumoto, Durability Enhancement effect of silica fume on the bond behavior of concrete-PCM composites under environmental conditions, *Polymers* vol. 15 (9) (2023), <https://doi.org/10.3390/polym15092061>.
- [30] H. Zhao, Y. Hu, Z. Tang, K. Wang, Y. Li, W. Li, Deterioration of concrete under coupled aggressive actions associated with load, temperature and chemical attacks: a comprehensive review, *Constr. Build. Mater.* vol. 322 (2022) 126466, <https://doi.org/10.1016/j.conbuildmat.2022.126466>.
- [31] G.D. Bowden, B.J. Pichler, A. Maurer, A design of experiments (DoE) approach accelerates the optimization of copper-mediated 18F-fluorination reactions of arylstannanes, *Sci. Rep.* vol. 9 (1) (2019) 11370, <https://doi.org/10.1038/s41598-019-47846-6>.
- [32] S. Zahraee, G. Rezaei, A. Memari, J. Afshar, and J. Mohd Rohani, *Teaching Design of Experiment and Response Surface Methodology Using Paper Helicopter Experiment*. 2013.
- [33] I.K. Shalabh "Chapter 4: Experimental Design and Their Analysis," *Anal. Var.*, pp. 1–312016.
- [34] S.S. Wu, B.Z. Li, J.G. Yang, S.K. Shukla, Predictive modeling of high-performance concrete with regression analysis, *IEEE Int. Conf. Ind. Eng. Eng. Manag.* 2010 (2010) 1009–1013, <https://doi.org/10.1109/IEEM.2010.5674229>.
- [35] M. Tanco, E. Viles, L. Ilzarbe, M.J. Alvarez, Is design of experiments really used? A survey of Basque industries, *J. Eng. Des. - J. Eng. Des.* vol. 19 (2008) 447–460, <https://doi.org/10.1080/09544820701749124>.
- [36] A. Poorarabi, M. Ghasemi, M. Azhdary Moghaddam, Concrete compressive strength prediction using non-destructive tests through response surface methodology, *Ain Shams Eng. J.* vol. 11 (4) (2020) 939–949, <https://doi.org/10.1016/j.asej.2020.02.009>.
- [37] M.B. Khan, A. Waqar, N. Bheel, N. Shafiq, and N.H. Sor, "Optimization of fresh and mechanical characteristics of carbon fiber-reinforced concrete composites using response surface technique," pp. 1–32, 2023.
- [38] B.W. Chong, R. Othman, T. Sheng, R. Putra Jaya, M.M.A.B. Abdullah, Properties of mortar with waste tyre rubber as partial sand replacement, *Key Eng. Mater.* vol. 879 (2021) 49–61, <https://doi.org/10.4028/www.scientific.net/KEM.879.49>.
- [39] A.N. Rizalman and C. C. Lee, Comparison of Artificial Neural Network (ANN) and Response Surface Methodology (RSM) in Predicting the Compressive Strength of POFA Concrete," vol. 4, pp. 210–216, 2020, [Online]. Available: <http://arqiiipubl.com/ams>.
- [40] N.I. Rahim, B.S. Mohammed, I. Abdulkadir, M. Dahim, Effect of crumb rubber, fly ash, and nanosilica on the properties of self-compacting concrete using response surface methodology, *Materials (Basel)* vol. 15 (4) (2022), <https://doi.org/10.3390/ma15041501>.
- [41] W. Lokuge, A. Wilson, C. Gunasekara, D.W. Law, S. Setunge, Design of fly ash geopolymer concrete mix proportions using Multivariate Adaptive Regression Spline model, *Constr. Build. Mater.* vol. 166 (2018) 472–481, <https://doi.org/10.1016/j.conbuildmat.2018.01.175>.
- [42] A.T. Nair, A. Makwana, M. Ahammed, The use of response surface methodology for modelling and analysis of water and wastewater treatment processes: a review, *Water Sci. Technol.* vol. 69 (2014) 464–478, <https://doi.org/10.2166/wst.2013.733>.
- [43] A. Waqar, et al., Effect of volcanic pumice powder ash on the properties of cement concrete using response surface methodology, *J. Build. Pathol. Rehabil.* vol. 8 (1) (2023), <https://doi.org/10.1007/s41024-023-00265-7>.
- [44] N. Abbas, M. Saad, M. Habib, Impact of carbon fibers on mechanical and durability properties of self-compacting concrete, *Eng. Proc.* vol. 22 (1) (2022), <https://doi.org/10.3390/engproc202202009>.
- [45] O. Petruška, J. Zajac, V. Molnár, G. Fedorko, J. Tkáč, The effect of the carbon fiber content on the flexural strength of polymer concrete testing samples and the comparison of polymer concrete and U-shaped steel profile damping, *Materials (Basel, Switz.)* vol. 12 (12) (2019), <https://doi.org/10.3390/ma12121917>.
- [46] M. Bashir, M. Kaushal, 2022, "Investigation on Carbon Fiber Based Concrete with Use of Silica Fume," no. 3, pp. 299–308.
- [47] F. Collins, Inclusion of carbonation during the life cycle of built and recycled concrete: Influence on their carbon footprint, *Int. J. Life Cycle Assess.* vol. 15 (6) (2010) 549–556, <https://doi.org/10.1007/s11367-010-0191-4>.
- [48] P.S.M. Thilakarathna, S. Seo, K.S.K. Baduge, H. Lee, P. Mendis, G. Foliente, Embodied carbon analysis and benchmarking emissions of high and ultra-high strength concrete using machine learning algorithms, *J. Clean. Prod.* vol. 262 (2020) 121281, <https://doi.org/10.1016/j.jclepro.2020.121281>.
- [49] B.R. Cushman, Energy consumption Energy type," pp. 1–12, 2017, [Online]. Available: <http://www.dartmouth.edu/~cushman/books/Numbers/Chap1-Materials.pdf>.
- [50] L.K. Turner, F.G. Collins, Carbon dioxide equivalent (CO₂-e) emissions: a comparison between geopolymer and OPC cement concrete, *Constr. Build. Mater.* vol. 43 (2013) 125–130, <https://doi.org/10.1016/j.conbuildmat.2013.01.023>.
- [51] R. Kumar, N. Shafiq, A. Kumar, A.A. Jhatial, Investigating embodied carbon, mechanical properties, and durability of high-performance concrete using ternary and quaternary blends of metakaolin, nano-silica, and fly ash, *Environ. Sci. Pollut. Res.* vol. 28 (35) (2021) 49074–49088, <https://doi.org/10.1007/s11356-021-13918-2>.
- [52] R. Jones, M. McCarthy, and M. Newlands, "Fly Ash Route to Low Embodied CO₂ and Implications for Concrete Construction," *World Coal Ash Conf.*, 2011.
- [53] A. Waqar, K. Skrzypkowski, H. Almujiabah, K. Zagórski, and M.B. Khan, Success of Implementing Cloud Computing for Smart Development in Small Success of Implementing Cloud Computing for Smart Development in Small Construction Projects," no. May, 2023, doi: 10.3390/app13095713.
- [54] A. Waqar, M.B. Khan, N. Shafiq, K. Skrzypkowski "Assessment of Challenges to the Adoption of IOT for the Safety Management of Small Construction Projects in Malaysia: Structural Equation Modeling applied sciences Assessment of Challenges to the Adoption of IOT for the Safety Management of Small Constr," no. March, 2023, doi: 10.3390/app130533402023.
- [55] C. Kennedy, N. Bheel, G. Nadeem, O. Benjeddou, and A. Waqar, "Efficiency of Ficus sycamoros exudates as corrosion inhibitor for mild steel pipes in acid concentrated water and soil," 2023.

- [56] A. Waqar, H. Almujiabah "Factors Influencing Adoption of Digital Twin Advanced Technologies for Smart City Development: Evidence from Malaysia," no. March, 2023, doi: 10.3390/buildings130307752023.
- [57] A. Waqar, I. Othman, H. Almujiabah, M.B. Khan, S. Alotaibi, A.A.M. Elhassan, Factors influencing adoption of digital twin advanced technologies for smart city development: evidence from Malaysia, Buildings vol. 13 (3) (2023) 775, <https://doi.org/10.3390/buildings13030775>.
- [58] I. Abdulkadir, B.S. Mohammed, M.S. Liew, M.M.A. Wahab, Modelling and multi-objective optimization of the fresh and mechanical properties of self-compacting high volume fly ash ECC (HVFA-ECC) using response surface methodology (RSM), Case Stud. Constr. Mater. vol. 14 (2021) e00525, <https://doi.org/10.1016/j.cscm.2021.e00525>.
- [59] H. Tahir, M.B. Khan, N. Shafiq, D. Radu, and M.H. Nyarko, "Optimisation of Mechanical Characteristics of Alkali-Resistant Glass Fibre Concrete towards Sustainable Construction sustainability Optimisation of Mechanical Characteristics of Alkali-Resistant Glass Fibre Concrete towards Sustainable Construction," no. July, 2023, doi: 10.3390/su151411147.