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Predictive analysis of mechanical characteristics in sustainable hybrid concrete made with coconut fibre, manufactured sand and expanded clay aggregates.

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ABSTRACT :

This study focuses on the predictive analysis of mechanical characteristics in sustainable hybrid concrete made with coconut fiber, manufactured sand (M-sand), and expanded clay aggregates.The utilization of these sustainable alternatives addresses the environmental concerns associated with conventional concrete constituents, specifically by incorporating an agricultural waste (CF), a quarry byproduct (MS), and a lightweight aggregate (ECA).The primary objective was to assess the impact of varying proportions of these sustainable materials on key mechanical properties namely compressive strength, split tensile strength, and flexural strength and to develop predictive models for optimization.The aim is to develop a concrete mix that balances structural performance with environmental sustainability by utilizing alternative materials.Coconut fibre was used as a reinforcing material, M-sand replaced fine aggregate, and expanded clay replaced coarse aggregate partially by weight. The hybrid mix design integrates coconut fibres as a natural reinforcement to improve tensile strength, ductility, and crack resistance, a known benefit in fibre-reinforced concrete. Manufactured sand (M-Sand) is used to replace natural river sand, offering a more consistent and sustainable fine aggregate with excellent particle shape and grading that enhances bonding. Expanded clay aggregates (ECA) are incorporated to reduce the concrete's density, making it a lightweight concrete suitable for structural applications with reduced dead loads.Experimental investigations were conducted on M25 grade concrete to evaluate compressive strength, split tensile strength, and flexural strength at 28 days.This project not only aims to develop an innovative, high-performance concrete by effectively utilizing industrial waste and byproducts but also addresses critical environmental concerns like the depletion of natural resources and waste management.The Response Surface Methodology (RSM), specifically using a Central Composite Design (CCD), was employed to minimize the number of experimental mixes. The results demonstrated that while the inclusion of ECA reduced the concrete density (achieving a lightweight status), the mechanical properties were significantly influenced by the complex interactions between the constituents.

Keywords: Sustainable concrete, Coconut fibre, Manufactured sand, Expanded clay aggregates,Response surface methodology (RSM-CCD).

INTRODUCTION

Concrete has evolved from simple lime–pozzolana binders to modern OPC-based systems that have enabled the construction of durable and complex infrastructure.Over the years, the rapid growth of the construction industry and the reliance on naturally available raw materials have raised major sustainability concerns. Excessive extraction of natural resources has led to ecological imbalance, depletion of reserves, and increased environmental footprint.The construction industry faces a critical need to transition toward sustainable and eco-friendly materials to mitigate environmental impacts, particularly those associated with the production of conventional cement and the depletion of natural aggregates. This study introduces a novel eco-friendly concrete formulation that integrates coconut fibre (CF) as a natural reinforcement, manufactured sand (M-sand) as a fine aggregate replacement, and expanded clay aggregates (ECA) for lightweight properties. Each component is strategically chosen to enhance both the concrete's sustainability and its mechanical performance: CF improves tensile strength and crack resistance due to its high toughness; M-sand reduces reliance on quarried river sand; and ECA decreases the dead load of the structure.This study investigates a novel and locally viable sustainable hybrid concrete system, defined by the synergistic integration of coconut fibre (CF), manufactured sand (M-sand), and expanded clay aggregates (ECA). The introduction can be further expanded to detail the specific challenges and opportunities presented by each material, and to more deeply establish the necessity for a predictive approach in this interdisciplinary field.The global construction sector is actively pursuing sustainable and circular economy principles to drastically lower its substantial environmental footprint, primarily driven by the energy-intensive production of ordinary Portland cement and the unsustainable extraction of natural aggregates. This necessity has galvanized research into developing hybrid concrete systems that responsibly incorporate agricultural and industrial by-products. This study investigates a novel and locally viable sustainable hybrid concrete system, defined by the synergistic integration of coconut fibre (CF), manufactured sand (M-sand), and expanded clay aggregates (ECA).The deliberate selection of these three components addresses distinct material science and environmental challenges. Coconut Fiber (CF), an abundant waste from coconut processing, is incorporated primarily as a natural micro-reinforcement. While its low modulus of elasticity typically reduces compressive strength, its high content and excellent toughness significantly enhance the concrete's ability to resist crack propagation, thereby improving its flexural strength, split tensile strength, and energy absorption capacitycritical properties for durable structures. Simultaneously, the use of Manufactured Sand (M-sand), produced by crushing rock, serves as a crucial, sustainable replacement for river sand, combating widespread illegal dredging and resource depletion. M-sand's angular shape and controlled grading also offer distinct advantages in concrete workability and packing density compared to the rounded grains of natural sand. Finally, Expanded Clay Aggregates (ECA) are utilized to produce Lightweight Aggregate Concrete (LWAC). ECA's porous structure drastically reduces the concrete's bulk density, offering benefits such as reduced dead loads, decreased foundation costs, and enhanced thermal insulation, a key feature for energy-efficient buildings.The resulting hybrid material is characterized by a complex interplay of properties: the low density of ECA, the intricate micro-cracking resistance of CF, and the superior packing of M-sand. This complexity makes traditional trial-and-error mix design inefficient and costly. Therefore, the core of this research lies in the application of predictive analysis techniques.The predictive analysis approach is used to evaluate and optimize the mechanical characteristics of this hybrid concrete. By employing statistical tools such as Response Surface Methodology (RSM), the relationships between the material proportions and mechanical properties such as compressive, split tensile, and flexural strength can be effectively analyzed and predicted. This study aims to develop a sustainable, lightweight, and high-performance concrete mixture that minimizes environmental impact while maintaining or improving the mechanical behavior of conventional concrete. To address these issues, research has progressively shifted toward the development of sustainable and high-performance concretes. Modern studies focus on incorporating alternative binders, eco-friendly aggregates, natural and synthetic reinforcements, industrial by-products, and advanced chemical admixtures**.** Alongside these material innovations, optimization techniques and predictive modelling tools have been introduced to minimize conventional trial-and-error approaches and to designconcretes that are both resource-efficient and structurally reliable.

RESPONSE SURFACE METHODOLOGY

Response Surface Methodology (RSM) is a statistical and mathematical technique used for developing, improving, and optimizing processes in which several input variables influence one or more output responses. It helps to analyse the relationship between the input parameters and the desired output, enabling prediction and optimization of results efficiently.When performing Response Surface Methodology (RSM) with a Central Composite Design (CCD), specialized statistical software is essential for generating the design matrix, analysing the experimental data, and creating the response surface plots.

Central Composite Design (CCD) is one of the popular experimental designs used in RSM to efficiently model and analyse the response surface.The use of Response SurfaceMethodology (RSM) software with the Central Composite Design (CCD) is essential for efficiently optimizing processes and systems. The software first allows a user to designthe CCD experiment by defining the experimental factors and their low/high levels, automatically generating the structured set of experimental runs.

Using Response Surface Methodology (RSM) with a Central Composite Design (CCD) allows software to optimize complex processes by modelling the relationships between multiple input variables and an outcome.In concrete research, RSM using CCD is applied to optimize the mix proportions such as cement content, aggregate ratios, fibre percentage, and water–cement ratio to achieve desired mechanical properties like compressive, tensile, and flexural strength.

Variables	Minimum	Maximum
Coconut fibres	0.2	1.5
Manufactured sand	30	100
expanded clay aggregates.	0	30

Table. 1 Levels of variables

MATERIAL DATA

Coconut Fiber

Coconut Fiber (Coir) is an agricultural waste product used as a natural, low-cost fiber reinforcement to improve the mechanical properties of the concrete, particularly flexural strength, tensile strength, and toughness (energy absorption capacity). As one of the toughest natural fibers, it helps in arresting micro-cracks and reducing crack propagation, which enhances the post-cracking behavior and ductility of the material.

Manufactured Sand (M-Sand)

Manufactured Sand (M-Sand) serves as a sustainable fine aggregate that replaces natural river sand, addressing environmental concerns related to sand mining. Produced from crushed rock, M-Sand is generally well-graded and, when properly processed, can lead to higher compressive strength in concrete compared to natural sand.

Expanded Clay Aggregates

Expanded Clay Aggregates (ECA), also known as lightweight expanded clay aggregate (LECA), are a type of lightweight coarse aggregate. ECA is produced by heating clay to high temperatures, causing it to expand and form porous, low-density granules. The primary function of ECA in this project is to significantly reduce the overall density of the concrete, thereby decreasing the dead weight of the structure.

TEST METHODS

The primary mechanical characteristics of this hybrid concrete are investigated using three main tests on hardened samples, along with a workability test for the fresh mix. To determine the concrete's ability to resist crushingits most fundamental measure of qualitythe Compressive Strength Test is performed on standard cubes. To assess how well the coconut fibres prevent the concrete from cracking when pulled, the Split Tensile Strength test is conducted on cylinder samples. Finally, to measure the concrete's resistance to bending or breaking in a beam or slab, the Flexural Strength Test is carried out on rectangular prisms. Before these strength tests, the Slump Test is essential for the fresh mix to check its workability (how easy it is to mix and place), ensuring the combination of manufactured sand and lightweight expanded clay aggregates results in a usable material. The predictive analysis then uses the data from these testsmeasuring the strength after set curing periods, typically 28 days to figure out the best combination of sustainable materials that produces the highest-performing, lightweight concrete.

RESULTS AND DISCUSSION:

COMPRESSIVE STRENGTH

The compressive strength of eco-engineered concrete was found to vary significantly with the proportions of *coconut fiber manufactured sand* , *expanded clay aggregates* . Among the twenty different mixes tested, the highest compressive strength of *47.49 MPa* was achieved for the mix containing *1.5% CF, 30% MS, and 0% ECA*, corresponding to an estimated ultimate load-carrying capacity of about *1,068 kN* for a standard 150 mm cube specimen. This indicates that moderate inclusion of coconut fibre and partial replacement of natural sand with manufactured sand enhances both the bonding and packing density of the concrete. The addition of MS improves the inter-particle contact and reduces voids within the mix, resulting in a dense matrix with superior load-bearing ability. Coconut fibres, due to their high tensile capacity and rough surface texture, help in controlling micro-crack propagation and improve post-cracking behavior, contributing to higher compressive values. However, when the percentage of expanded clay aggregate increases (especially beyond 15–20%), the concrete becomes more porous and lightweight, leading to a gradual decrease in strength. The minimum compressive strength observed was *18.23 MPa* for the mix with *1.5% CF, 30% MS, 30% ECA***,** equivalent to a load of *411 kN***,** which clearly shows the adverse influence of excessive ECA.Overall, the results demonstrate that *balanced proportions of CF and MS*, with minimal inclusion of ECA, yield optimal compressive performance. Excess fibre or lightweight aggregates disrupt the matrix continuity and reduce the compactness of the concrete. Hence, the synergy between CF and MS is crucial to achieving high-strength, sustainable, and eco-friendly concrete with desirable mechanical properties.

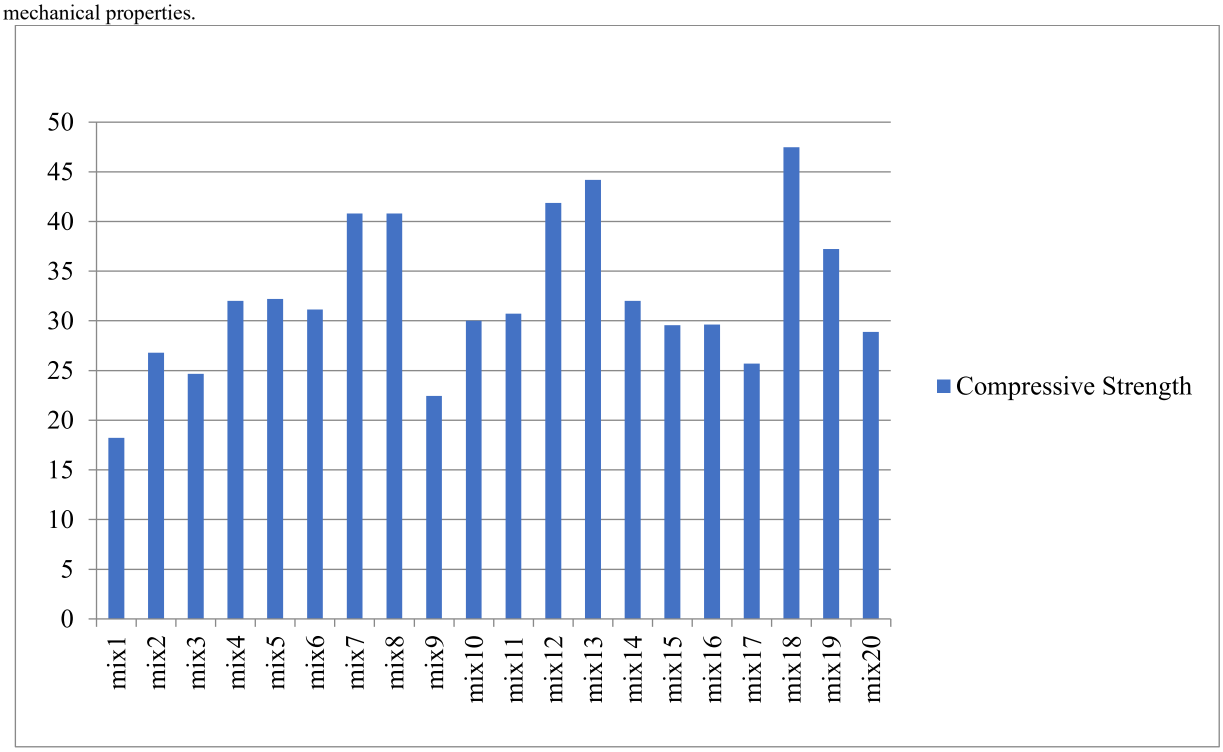


Figure 1: Compressive Strength Test

This bar chart represents the *compressive strength* of 20 different concrete mix proportions (Mix1–Mix20) obtained from experimental tests. The variations in bar heights indicate differences in strength values depending on the combination of materials such as coconut fibre, manufactured sand, and expanded clay aggregates. Some mixes, like Mix7, Mix13, and Mix18, show higher strength values, suggesting optimal material proportions. In contrast, mixes such as Mix1 and Mix9 exhibit lower strengths, indicating less favorable combinations. Overall, the graph helps to identify the mix ratios that provide maximum Compressive Strength of Concrete.

SPLIT TENSILE STRENGTH

The split tensile strength results revealed the influence of fibre content and aggregate composition on the concrete's tensile performance. The highest tensile strength of 16.07 MPa was obtained for the mix containing 0.2% CF, 100% MS, and 0% ECA, where the fibres were optimally distributed, enhancing the material's ability to resist crack initiation and propagation. This significant increase demonstrates the effectiveness of coconut fibre as a bridging material between cracks, which helps absorb tensile stresses that usually lead to brittle failure in plain concrete. Moderate inclusion of CF enhances the interfacial bonding between the matrix and fibres, improving energy absorption and tensile capacity. The use of 100% manufactured sand also contributed positively due to its angular particle shape, providing better mechanical interlock and frictional resistance than natural sand. Conversely, mixes with higher ECA content exhibited lower tensile strengths, the minimum being 5.39 MPa, mainly due to the weak bond strength between the lightweight aggregates and the cement paste. The overall range of split tensile strength values indicates that controlled addition of CF (0.2–1%) and complete replacement of natural sand with MS can significantly enhance tensile resistance. However, excessive ECA or fibre content leads to non-uniform fibre dispersion and poor matrix bonding, resulting in lower tensile efficiency. Thus, an optimized CF–MS blend without ECA provides the most effective tensile performance for eco-engineered concrete.

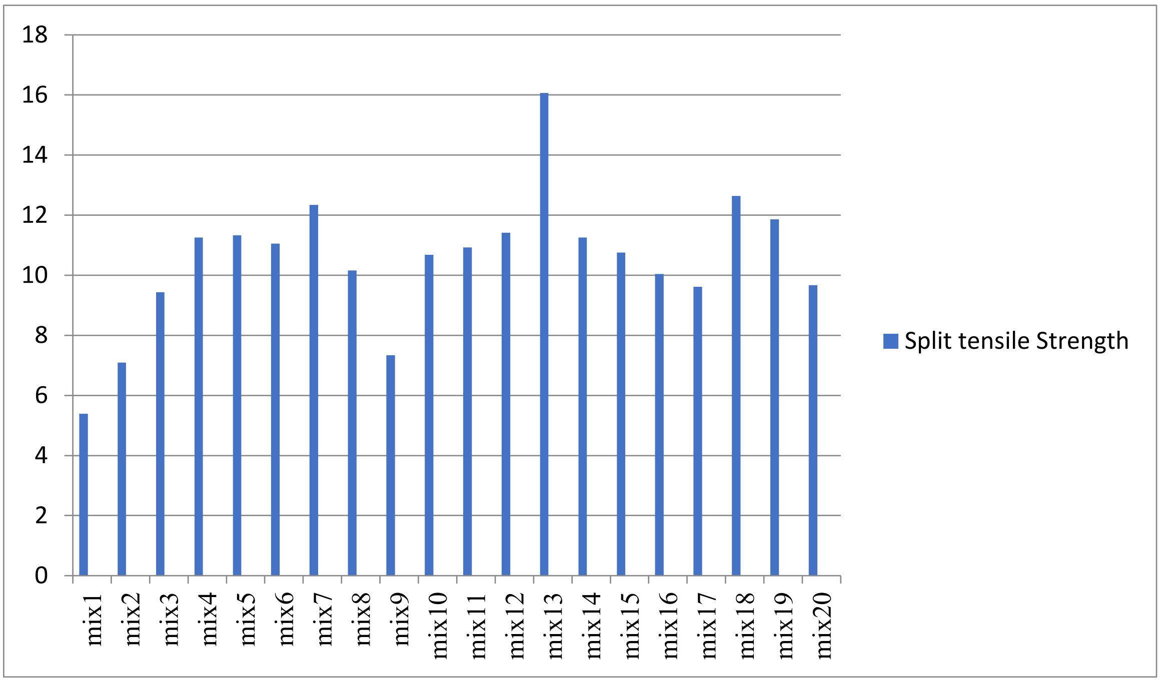


Figure 2: Split Tensile Strength Test

This bar chart illustrates *split tensile strength* values for twenty different concrete mix proportions (M1–M20). Thevariation in the bar heights shows how the tensile capacity of the concrete changes with the proportion of coconut fibre, manufactured sand, and expanded clay aggregates. Mixes such as M7, M13, and M18 exhibit comparatively higher tensile strength, indicating improved bonding and crack resistance due to fibre reinforcement. Lower values in some mixes suggest weaker tensile behaviour caused by improper material balance. Overall, the results highlight the mixes that enhance tensile performance and ductility in sustainable hybrid concrete.

FLEXURAL STRENGTH TEST

Flexural strength results varied between 5.0 MPa and 7.0 MPa, highlighting the impact of mix composition on the beam's bending and cracking behaviour. The maximum flexural strength of 7.0 MPa was observed in mixes with 0.2% CF, 100% MS, and 0% ECA, as well as 0.2% CF, 30% MS, and 0% ECA. These combinations exhibited superior load redistribution and crack resistance under flexural loading conditions. The inclusion of a small amount of coconut fibre improves ductility and toughness, allowing the concrete to sustain higher loads before failure. Manufactured sand further enhances flexural performance by increasing particle friction and interlocking within the matrix, leading to better stress transfer across cracks. In contrast, an increase in ECA content was found to reduce flexural strength due to the lower stiffness and higher porosity of the aggregates, which weaken the concrete under bending. Mixes with higher ECA proportions typically recorded flexural strengths of around 5.0 MPa, indicating limited resistance to flexural tension. In summary, the findings suggest that coconut fibre plays a vital role in improving post-cracking behaviour and flexural toughness, while manufactured sand ensures structural integrity by enhancing bond strength. When ECA is used beyond the optimal range, the flexural capacity declines due to its lightweight nature. Therefore, the combination of 0.2–1.0% CF with 30–100% MS and low ECA content produces a well-balanced concrete with improved flexural behaviour and higher energy absorption capacity.

The bar chart displays the *flexural strength* of the twenty concrete mixes (M1–M20), reflecting their ability to resist bending stresses. Noticeable variations are observed across the mixes, showing the influence of different material combinations on flexural performance. Mixes like M12, and M13 show higher flexural strength, suggesting better load distribution and crack resistance due to effective fibre and aggregate interaction. In contrast, mixes with lower strength indicate reduced flexibility and toughness. Overall, the results emphasize the optimal mixes that contribute to improved bending performance and structural efficiency.

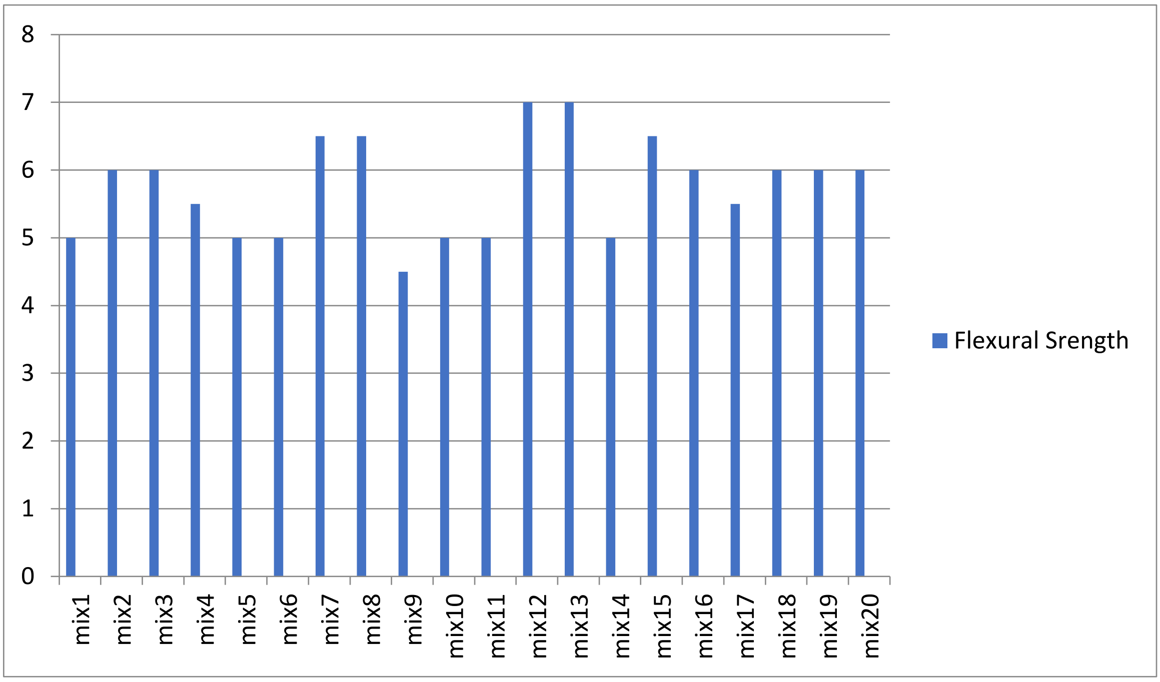


Figure 3: Flexural Strength Test

RSM MODEL

The investigation was conducted to study the influence of coconut fibre, manufactured sand, and expanded clay aggregates on the prediction of compressive, split tensile, and flexural strengths of sustainable hybrid concrete. The experimental work was designed using the Response Surface Methodology (RSM) based on the Central Composite Design (CCD) approach to establish a relationship between the input variables and the resulting mechanical properties. A total of twenty experimental runs were carried out, and specimens were prepared and tested after the required curing period to obtain accurate strength results. The obtained experimental data were analysed to develop regression equations for Compressive strength at 28 days (CS28), Split Tensile strength at 28 days (STS28) and Flexural strength at 28 days (FS28) in the form of second-order polynomial models, which describe the behaviour of each strength parameter in terms of the selected variables. These equations include linear, interaction, and quadratic effects that help in understanding how changes in coconut fibre, manufactured sand, and expanded clay aggregate contents influence the overall performance of concrete. The developed models provide a scientific basis for predicting and optimizing the strength characteristics, ensuring an economical and sustainable mix design for hybrid concrete.

CS28 = 47.83 + 2.3 (CF) - 0.170 (MS) - 0.992 (ECP) - 3.10 (CF*CF) + 0.00062 (MS*MS)
+ 0.0213 (ECP*ECP) + 0.0788 (CF*MS) - 0.216 (CF*ECP) - 0.00044 (MS*ECP)

STS28= 11.35 + 0.28(CF) + 0.010(MS) + 0.036(ECP) - 0.73(CF*CF) + 0.000133(MS*MS)
- 0.00071(ECP*ECP)+ 0.0070(CF*MS) - 0.0540(CF*ECP) - 0.00171(MS*ECP)

FS28 = 8.87 - 2.25 (CF) - 0.0524 (MS) - 0.0675 (ECP) + 0.377 (CF*CF) + 0.000334 (MS*MS)
+ 0.00071 (ECP*ECP) + 0.01648 (CF*MS) + 0.0256 (CF*ECP) - 0.000238 (MS*ECP)

PARETO CHART ANALYSIS

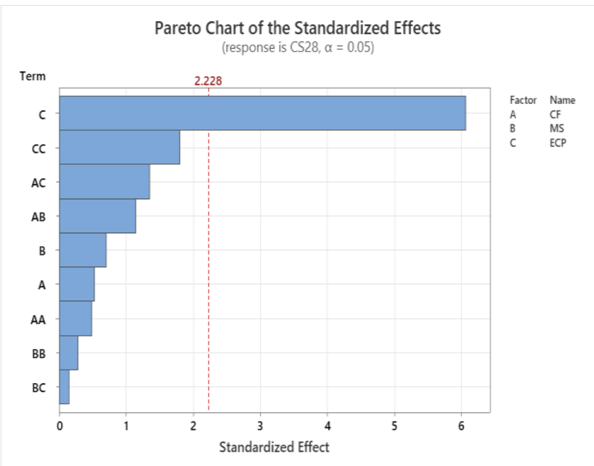


Figure 4: Pareto Chart for CS28

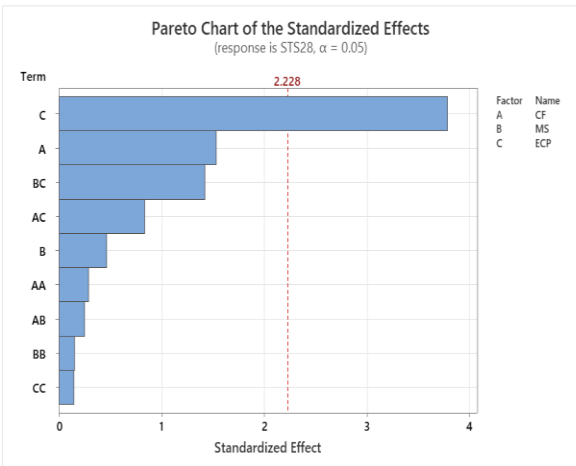


Figure 5: Pareto Chart for STS28

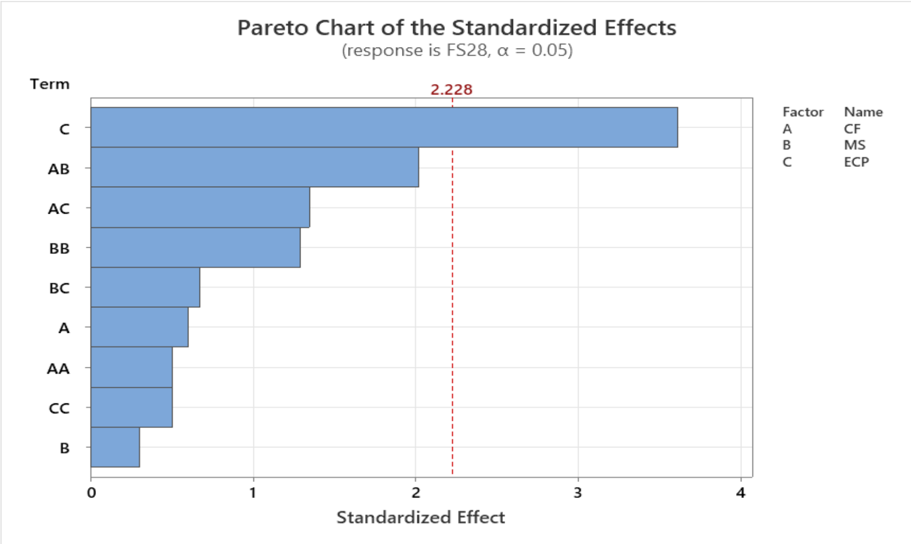
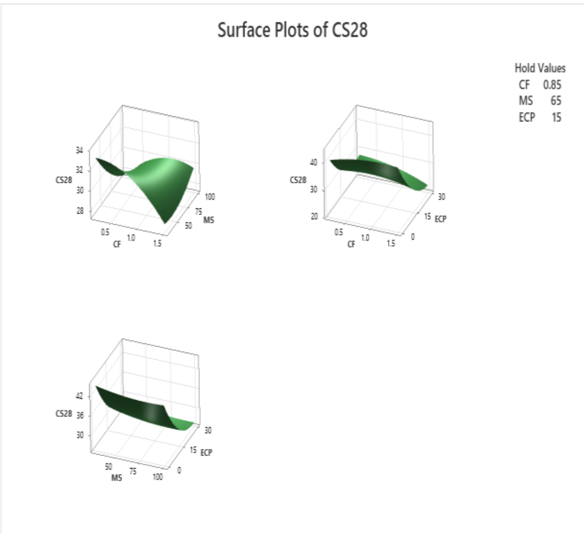


Figure 6: Pareto Chartfor FS28

The Pareto chart (Figure 4) clearly ranks ECP as the most dominant parameter, as its standardized effect surpasses the reference line representing statistical significance. CF and MS appear with smaller bar lengths, indicating that their individual effects are relatively moderate. Among the two-factor interactions, none exceed the significance threshold, demonstrating that the response is primarily governed by individual factors. The chart visually emphasizes that compressive strength is largely controlled by the proportion of lightweight aggregate used. The dominance of ECP in the Pareto ranking correlates well with the normal plot and regression output, confirming consistent interpretation across all analytical tools.The Pareto chart (Figure 5) ranks ECP as the factor with the highest standardized effect, followed by CF and MS, which have much smaller contributions. The strong effect of ECP highlights its predominant role in determining the splitting behaviour of hybrid concrete. The other terms, being below the significance threshold, indicate a balanced influence but not statistically dominant. The visual ranking supports the hierarchyECP > CF > MS.The Pareto chart (Figure 6) confirms that ECP has the largest standardized effect, followed by the CF×MS interaction, which exhibits a shorter but noticeable bar. This interaction implies that moderate fibre addition in conjunction with adequate M-Sand proportion slightly improves bending strength by enhancing crack control and interfacial bonding. All other terms lie below the significance reference line, suggesting they have secondary effects.

SURFACE PLOT ANALYSIS



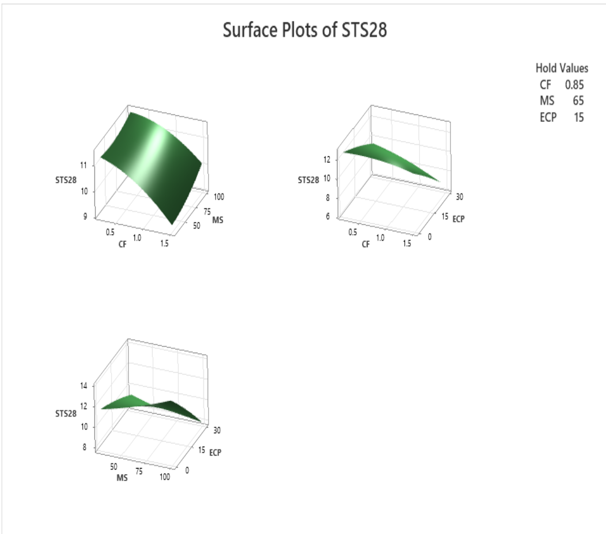


Figure 7: Surface Plot for CS28

Figure 8: Surface Plot for STS2

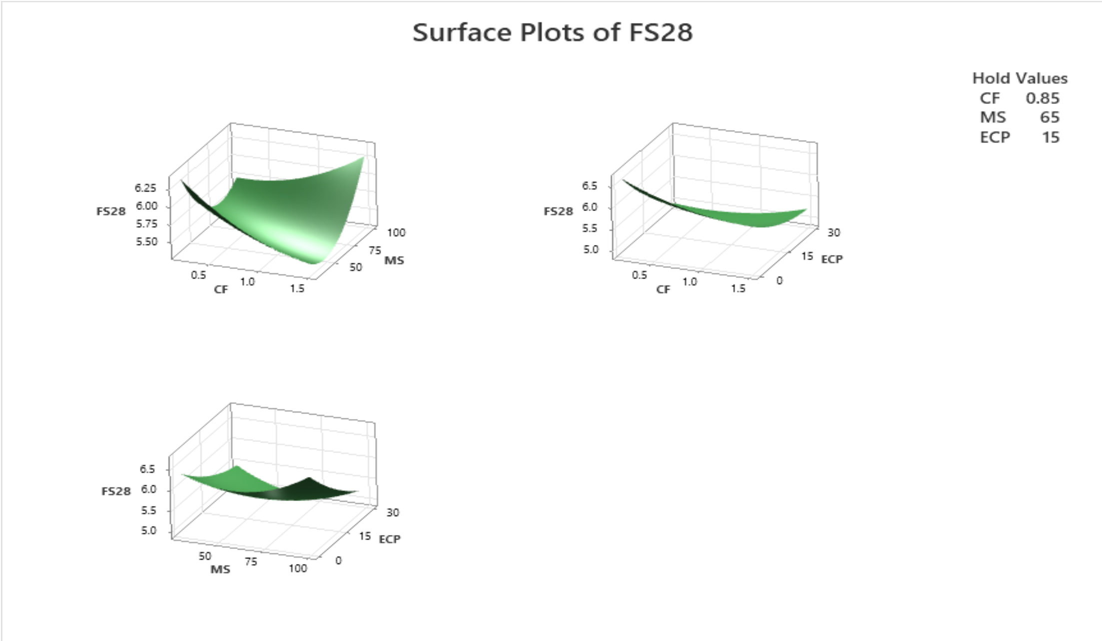


Figure 9: Surface Plot for FS28

The three-dimensional surface (Figure 7) portrays a smooth, downward-sloping trend of compressive strength from approximately 32 MPa to 26 MPa as ECP increases. The curvature of the surface confirms that the model captures the gradual non-linear variation. When CF and MS are simultaneously increased within their mid-range, a gentle rise in strength can be observed, which peaks at CF ≈ 1 % and MS ≈ 70 %, after which the response plateaus. This shows that additional fibre and manufactured sand enhance particle packing and fibre bridging up to a threshold, beyond which further addition does not significantly alter compressive resistance. The surface continuity and gentle curvature confirm uniform response behaviour across the studied range, illustrating that the regression model describes the data reliably. The 3D surface (Figure 8) for STS28 presents a regular plane with a mild decline along the ECP axis. The surface suggests that tensile strength decreases steadily from ≈ 10.8 MPa to ≈ 8.9 MPa with increasing ECP. For a fixed ECP value around 10 %, increasing CF from 0.5 % to 1.0 % results in a minor improvement of about 0.3–0.4 MPa, demonstrating the reinforcing action of coconut fibre. The smooth nature of the surface confirms predictable behaviour and validates the adequacy of the quadratic model in representing the response surface. The surface plot (Figure 9) displays a gently sloping surface descending along the ECP axis. Flexural strength decreases smoothly from about 5.5 MPa to 4.4 MPa as ECP increases, while CF and MS show smaller variations. The ridge of the surface, visible at moderate CF and MS, suggests that these two variables work together to marginally enhance flexural capacity. The smooth nature of the surface and absence of irregular peaks confirm that the system behaves consistently and that the model accurately represents the experimental response

CONTOUR PLOT ANALYSIS

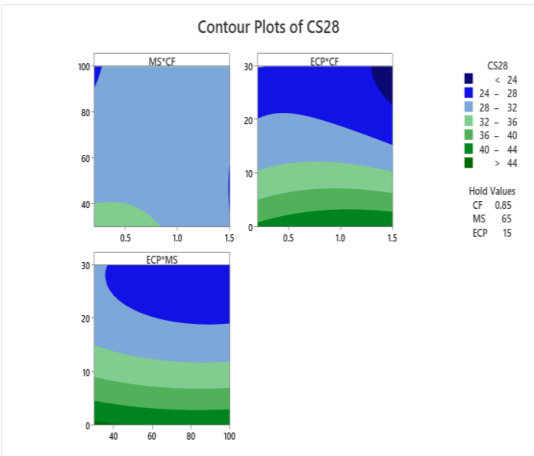


Figure 10: Contour Plot for CS28

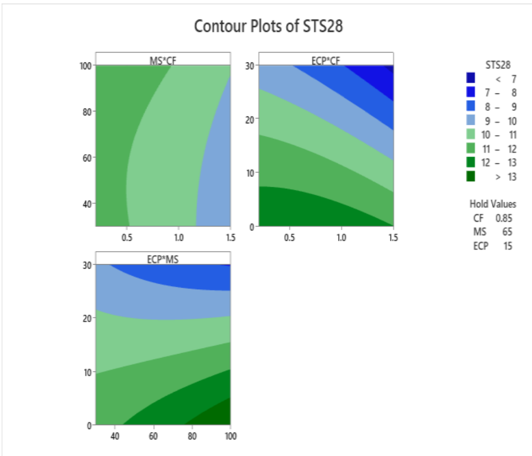


Figure 11: Contour Plot for STS28

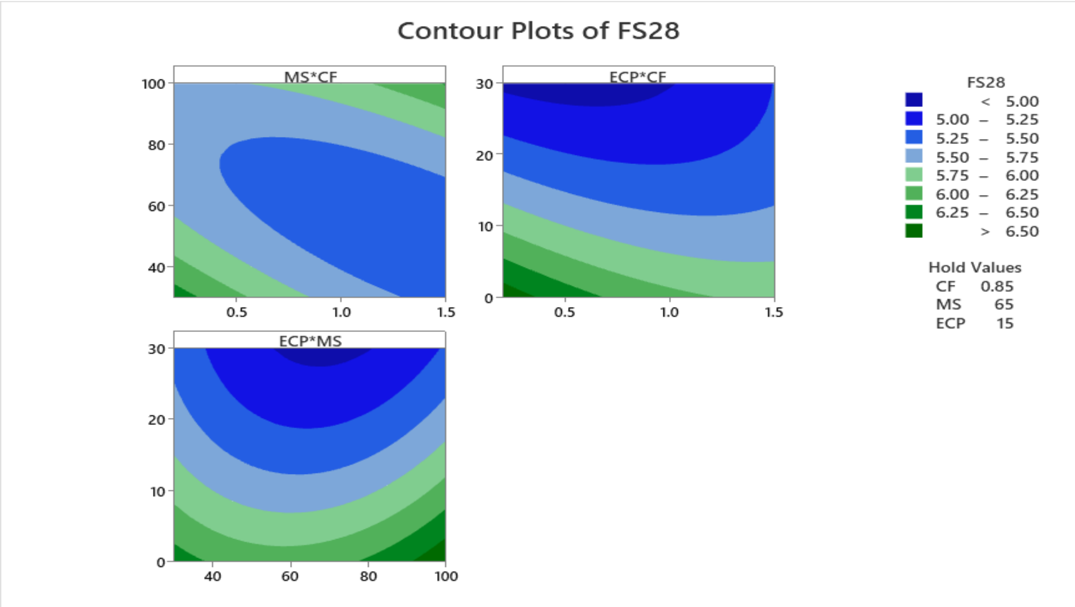


Figure 12: Contour Plot for CS28

The contour plots of CS28 (Figure 6) depict the combined influence of CF, MS, and ECP on compressive strength. The contours are more closely spaced along the ECP direction, highlighting its stronger effect compared with CF and MS. The highest strength zone, approximately 31–32 MPa, occurs at low ECP levels (5–10 %) combined with CF ≈ 1 % and MS ≈ 65–70 %. As ECP increases beyond 15–20 %, the response gradually decreases to 27–28 MPa, demonstrating that excessive lightweight aggregate replacement reduces the load-bearing capacity of the concrete matrix. The near-elliptical contour shapes suggest mild quadratic behaviour, implying that compressive strength decreases non-linearly with increasing ECP. The central region of the plot defines the optimum response area, where the balance among all three constituents produces the best performance. The contour map (Figure 6) for STS28 displays smoothly varying iso-response lines. The maximum tensile strength region (≈ 10.5–11 MPa) corresponds to ECP ≤ 10 % combined with CF ≈ 0.8–1.0 % and MS ≈ 65–70 %. As ECP increases toward 20 %, the contours shift gradually to lower strength levels (8.5–9 MPa). The smooth curvature of the contour lines indicates a uniform transition without abrupt variation, validating the good fit of the RSM model. The contour pattern also highlights that CF slightly improves tensile performance through crack-bridging, especially at low ECP content. The contour map (Figure 6) for FS28 illustrates that the highest flexural strength (≈ 5.3–5.5 MPa) is achieved when ECP ≤ 10 % with CF ≈ 1 % and MS ≈ 65–70 %. As ECP rises toward 20 %, the strength gradually reduces to ≈ 4.3–4.5 MPa. The contour lines are moderately curved, indicating that an appropriate balance of CF and MS can offset part of the reduction caused by ECP. The contour field clearly defines a region of optimum response near the central part of the design, reflecting the synergy between adequate fibre content and fine aggregate replacement.

CONCLUSION

The following results were reached after optimising the strength qualities of concrete including CF, MS and ECA using the Central Composite design of RSM:

1. The best compressive strength (47.49 MPa) was found with 1.5% coconut fibre, 30% manufactured sand, and 0% expanded clay aggregate, showing that moderate fibre and sand replacement improve strength.
2. The highest split tensile strength (16.07 MPa) was seen at 0.2% coconut fibre and 100% manufactured sand, proving that a small amount of fibre helps resist cracks effectively.
3. The best flexural strength (7.0 MPa) was obtained with 0.2% coconut fibre and 30–100% manufactured sand, which increased ductility and bending resistance.
4. When expanded clay aggregate was added beyond 15–20%, the strength decreased because it made the concrete lighter and more porous.
5. The RSM model successfully predicted how different material proportions affect strength, helping to find the best mix easily.
6. The optimum mix is around 1% coconut fibre, 60–70% manufactured sand, and below 10% expanded clay aggregate, giving strong, durable, and eco-friendly concrete.

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