Vol. 05, No. 02, pp. 41 –48 (2024)
ISSN: 2709-6904

JoCEF

JOURNAL OF CIVIL ENGINEERING FRONTIERS

www.jocivilef.org

Mechanical Properties of End-of-life Waste Tyres Steel Fibre Reinforced Concrete: RSM-Based Modelling and Optimisation

Abubakar Sabo Baba[1,*], Sule Yaman Mohammed[2] Yabagi Isah Abdullahi[2] Dzukogi Abubakar Alhassan[2]
[1]*Faculty of Engineering, Federal University Dutsinma, Katsina, Nigeria, asbaba1@fudutsinma.edu.ng*
[2]*School of Engineering, Department of Civil Engineering, Federal polytechnic, Bida, Niger State, Nigeria,*
yamansule39@gmail.com; abdullahifatrab1977@gmail.com; realsasman1@gmail.com

Abstract

The influence of fibres on the compressive strength of concrete is complex and is determined by the type, quantity, and characteristics of the fibres utilized in designing and forming the concrete. Designing fibre reinforced concrete (FRC) constituents is challenging and affects the concrete's performance and practicality. This study utilized response surface methodology (RSM) to optimize the properties of concrete containing steel fibre extracted from end-of-life tyres (ELTs). Face-cantered central composite design (FC-CCD) of RSM was used in the design of experiments (DOE) with aspect ratio (10-70) and volume fraction (0.5 % - 1.2 %) as the input variables. Three levels of each variable were used in forming the design matrix. The resulting concretes were then tested for slump and compressive strength at 7 and 28 days of curing. As the aspect ratio and volume fraction increased, slump values decreased, and 7- and 28-day compressive strength increased up to an aspect ratio of 45 and 1.0% volume fraction. Beyond an aspect ratio of 45 and 1.0% volume fraction, a declining trend in compressive strength at all curing ages was observed. The Analysis of Variance (ANOVA) revealed that the variables volume fraction and aspect ratio significantly affect the variability in the FRC models, with all models being statistically significant at the 95% level across all factor levels. A numerical optimization method was used to determine the optimal mix proportions for ELTFRC. The optimum response values were achieved by combining a 1.01% volume fraction and a 33.86 aspect ratio, resulting in a desirability of 0.73.

Keywords: *End-of-life, Waste tyres, Aspect Ratio, Volume Fraction, fibre Reinforced Concrete, Response Surfaces Methodology, Optimization.*

Received: June 21, 2024 / Accepted: August 26, 2024 / Online: August 28, 2024

I. INTRODUCTION

Globally, the vehicle manufacturing sector is booming. It is projected that by the year 2050, the number of automobiles manufactured will be about 2.4 billion [1]. This growth is associated with technological development, increases in income and standard of living, and urbanization [2]. Consequently, this development leads to high demand for large quantities of vehicle tyres, resulting in associated disposal problems [3], [4]. Recent reports show that worldwide tyres production is about 3 billion units annually [5], and about 1 billion tyres are used for replacement every year [6], generating more than 1.5 million tons of waste [7], with more than 1 billion stockpiled or abandoned, awaiting disposal [8]. This poses significant environmental and disposal challenges, requiring careful management of the large volume of waste generated.

The growing quantity of waste tyres and environmental concerns has prompted researchers to explore potential applications for this substantial resource and develop strategies to reduce the environmental impact caused by landfilling and open burning. Effectively managing waste tyres can lead to waste reduction, resource conservation, cost savings, and enhanced sustainability. Different approaches are employed to handle waste tyres, such as energy recovery, reuse or re-treading, utilizing tyres as fuel, pyrolysis, landfill disposal, and material recovery [9], [10], [11], [12], [13], [14], [15].

Although it remains a manufacturing secret, tyres composition by weight per cent (wt%) depends on technology and type, such as passenger, truck, or off-road vehicle tyres. The constituents are rubber 45.0-47.0%, carbon black 22.0-21.5%, additives 5.0-7.5%, textile 5.5%, zinc oxide 1.0-2.0%, sulphur 1.0%, and steel 16.5-21.5% [17], [18]. However, end-of-life waste tyres are mostly utilized as a low-cost fuel for

doi:10.38094/jocef50189

power plants and cement factories, used as fuel for kilns [19]. The steel fibre generally recovered from end-of-life tyres shredding, anaerobic thermal degradation, and cryogenic methods is employed as raw material in the construction industry [20], mostly as steel fibre reinforcement in concrete.

There are two major drawbacks of concrete that sometimes act as a hindrance to the uses of this material: brittleness and low tensile strength. SFRC has been used with some success in overcoming this drawback, in various civil engineering applications, for foundations, hydraulic structures, tunnel linings, bridge decks, slabs, refractory materials, shot Crete, and precast elements [21], [22]. "The initial cost of the concrete may be increased significantly by the addition of steel fibers, with 1% conventional steel fibers roughly doubling the cost of concrete" [23]. Such a cost factor has made researchers experiment with steel fibers from end-of-life tyres. In view of the fact that with increased vehicle usage there come increased urbanization and increased living standards, the area has attracted more interest among researchers in light of impacts on the necessity of balancing economic development with environmental protection. This may be achieved by the existence of steel fibres to improve mechanical strength, ductility, and toughness of concrete, which eventually leads to high-strength and high-ductility concrete [24].

However, findings by researchers indicate conflicting experimental results on the influence of steel fibre reinforcement in concrete (SFRC). The results show that the inclusion of fibres can contribute to compressive strength, ranging from insignificant or negligible increases to significant increases, while also reducing the workability of the concrete [25], [2]. The majority of researchers conclude that the inclusion of steel fibres in concrete improves its resistance to crack propagation, provides high impact resistance, and enhances the durability properties of concrete [26], [27], [2], [28].

Utilization of end-of-life tyres steel fibres (ELTSFs) in concrete to reduce the environmental impact of solid waste was investigated by [2]. Steel fibres from end-of-life waste tyres were used to improve the mechanical and durability properties of concrete by incorporating and varying the fibre length and volume fraction of ELTSFs in concrete. The results show that workability tends to decrease with an increase in fibre length and volume fraction. Concrete with a 10mm fibre length and a 0.5% volume fraction produced concrete with the highest slump. The concrete specimen with a 60mm fibre length and a 1.0% volume fraction, at a curing regime of 60 days, gives the optimum gain in compressive strength of 9.85% compared to the reference concrete.

In similar studies by [29], suggested that the choice of volume fraction in steel fibre-reinforced concrete typically falls within the range of 1% to 2.5%. [30] Stated that incorporating steel fibres of 0% to 1.5% into concrete enhances its mechanical properties. However, the application of steel fibres beyond a 2% volume fraction results in a loss of workability and the formation of a balling effect due to the excessive steel fibres [31], leading to concrete with undesirable properties.

Researchers from [32] highlighted that the aspect ratio (length/diameter), volume fraction, and distribution of fibres are key factors affecting the performance of steel fibre-reinforced concrete. [33] studied the influence of ELTSFs and industrially manufactured steel fibres (IMSFs) on the strength and flexural performance of reinforced concrete with fibres of a constant diameter of 1.00mm (constant aspect ratio). The volume fractions of 1.2%-3.6% and 0.5%-2.5% were used for ELTSFs and IMSFs, respectively, for the concrete specimen fabrication. It was observed that the strength and flexural toughness of the ELTSF-reinforced concrete (ELFRC) were lower compared to the industrial steel fibres. However, the addition of about 1%-2% more ELTSFs than IMSFs yielded concrete with similar performance in terms of strength and toughness.

Authors of [34] investigated the combined impact of the water-to-cement ratio, the tensile strength of steel fibres, and the volume fraction of fibres on the mechanical properties of steel fibre reinforced concrete (SFRC). They aimed to identify optimal design parameters to maximize the fracture energy of the concrete using Response Surface Methodology (RSM). It was observed that the water-to-cement ratio, directly affected the performance of the steel fibres. However, both the matrix strength and the tensile strength of the fibres should be considered as important factors in SFRC and in the optimisation criteria.

In a similar study [35] employed a multi-objective Response Surface Methodology (RSM) to optimize the fracture parameters of steel fibre reinforced concretes, aiming to achieve a more ductile behaviour compared to plain concrete. They studied the effects of the aspect ratio (L/d) and the volume fraction of steel fibres (V_f) on the fracture properties of concrete in bending by measuring the fracture energy (GF) and characteristic length (l_{ch}). A three-level full factorial experimental design and RSM were utilized for optimization. The findings indicate that the fibre volume fraction and aspect ratio significantly influence the fracture energy and characteristic length.

To this end, RSM was adopted in this study to optimise the properties of end-of-life tyres steel fibre reinforced concrete (ELTSFRC). RSM is a collection of mathematical and statistical techniques useful for the modelling and analysis of problems in which a response of interest is influenced by several variables [36], [37], [38], [39], [40], [41]. This tool is highly effective for optimizing chemical reactions in the engineering production processes. It was utilized to analyse the impact of aspect ratio and volume fraction to model and optimised the fibre reinforced concrete.

II. MATERIALS AND METHOD

A. *Materials*

The ingredients used for the study were cement, fine aggregate (sand), coarse aggregate (gravel), water, and waste tyres steel fibre.

a) *Cement:* Ashaka Portland cement brand, conforming to [42], was used in this research. The cement properties are shown in Table 1.

TABLE 1: CHEMICAL AND PHYSICAL PROPERTIES OF ASHAKA CEMENT

Chemical properties		
Oxide composition	**Weight (%)**	**Limit specified by BS 12 (1989)**
SiO_2	19.68	17 -25
Al_2O_3	6.44	3-8
Fe_2O_3	3.32	0.5-6.0
CaO	60.92	60-67
MgO	0.97	0.1-4.0
SO_3	2.28	1-3
K_2O	0.85	Combined alkalis (K_2O+Na_2O)
Na_2O	0.12	0.2-1.3
Physical properties		
Specific gravity	3.15	-
Blaine fineness (m^2/kg)	370	275
Loss on ignition(%)	1.0	1.2
Soundness(mm)	2.0	-
PH	12.40	-

b) *Fine and Coarse Aggregates:* The aggregates used in the study were tested to determine the specific gravity, bulk density, aggregate crushing value, aggregate impact value, and particle size distribution. The tests were conducted in accordance with [42], [43], [44], [45] specifications, respectively. The test results of the fine and coarse aggregates are presented in Table 2.

TABLE 2: PHYSICAL PROPERTIES OF COARSE AGGREGATE

Property	**Value**	
	Fine aggregate	**Coarse aggregate**
Specific Gravity	2.62	2.66
Bulk Density (Kg/m^3)	1528	1518
Aggregate Crushing value (%)	-	14.47
Aggregate Impact value (%)	-	14.95
Silt Content	4.26	-

c) *Water:* The water used for the experiments was from the metropolitan water supply.

d) *Waste tyres Steel Fibre:* The steel fibres used were extracted from waste truck tyres through a manual cutting process to obtain the waste tyres steel fibres (WTSF). The results of the physical properties of the waste tyres steel fibres are presented in Table 3.

TABLE 3: PHYSICAL PROPERTIES OF WTSF

Property	**Description**
Average Diameter (mm)	0.92
Tensile strength	1260
Shape	Cylindrical
Colour	Black

B. Method

a) *Experimental Design (DOE) and Concrete Mix Preparations:* The multi-objective simultaneous optimization method was applied to optimize the aspect ratio and volume fraction of ELSFRC, considering slump and 7 and 28 day compressive strength as responses. Face-cantered RSM was used in designing the experimental combinations. The independent variables considered were three levels (10, 45, and 70) of the aspect ratio of WTSF, as shown in Table 4, and the resulting design matrix in Table 5. Experimental data were collected to build the RSM models, and a comparison was then made between the experimental data and the data from the fitted models. The fitted models were used in the optimization process, which was conducted using the numerical desirability method based on ELSFRC goals and limits.

TABLE 4: INDEPENDENT VARIABLES, RESPONSES, UNITS AND DATA RANGE

Designation	**Data Band**
Aspect ratio	$0.5 \leq X1 \leq 2.0$
Volume fraction (%)	$10 \leq X2 \leq 70$
Slump (mm)	$20 \leq Y1 \leq 38$
7-days CS (N/mm^2)	$16.34 \leq Y2 \leq 29.99$
28-days CS (N/mm^2)	$29.00 \leq Y3 \leq 37.43$

TABLE 5: VARIABLES COMBINATIONS (MATRIX)

S/NO.	**Aspect Ratio (X1)**	**Volume Fraction (X2)**	**Slump (mm)**	**7-days CS (days)**	**28-days CS (days)**
1	2.00	45	28	18.06	37.43
2	1.0	45	25	26.37	34.33
3	0.5	70	25	26.87	29.00
4	1.0	45	25	26.37	34.33
5	1.0	45	25	26.37	34.33
6	1.0	10	25	29.99	33.00
7	1.0	45	25	26.37	34.33
8	1.0	70	23	22.69	31.57
9	0.5	10	38	28.23	31.00
10	1.0	45	25	26.37	34.33
11	2.0	10	28	21.01	29.20
12	2.0	70	20	16.34	33.22
13	0.5	45	30	29.74	31.00

b) *Concrete Mix Preparations*: The grade of concrete adopted for this study was M-25, which corresponds to a 28 day compressive strength of 25 N/mm². The American Concrete Institute (ACI) [46] method of mix design was used to determine the required proportion of the constituent materials. The summary of the mix proportions of the constituent materials used for the production of waste tyres steel fibre concrete is presented in Table 6.

TABLE 6: MIX PROPORTIONS OF CONSTITUENT MATERIALS USED FOR WTSF CONCRETE PRODUCTION

Mix ID	**Cement (Kg/m3)**	**F/A (Kg/m3)**	**C/A (Kg/m3)**	**Water (Kg/m3)**	**WTSF Vf (%)**
V_f - 0.00	385	663	1170	185	0.0
V_f - 0.5	385	663	1170	185	0.5
V_f - 1.0	385	663	1170	185	1.0
V_f - 2.0	385	663	1170	185	2.0

c) Slump Test: The slump test for control concrete and ELTSFCs was conducted accordance with BS [47] standard. The ELTSF was incorporated into the concrete production using the DOE, as tabulated in Table 7 below.

TABLE 7: SLUMP TEST RESULTS

Vf (%)	**Aspect Ratio**	**Slump (mm)**			**Average slump**
		1	**2**	**3**	
Control concrete		45	47	43	45
0.5	10	37	38	39	38
	45	31	30	30	30
	70	23	27	25	25
1.0	10	27	33	30	30
	45	28	26	32	28
	70	21	25	22	23
2.0	10	30	27	26	28
	45	27	24	24	25
	70	20	20	21	20

d) *Compressive Strength Tests:* Compressive strength tests were performed on concrete hardened cubes of size 100mm x 100mm x 100mm, cured for 7 and 28 days. The experiment was carried out using the ELE digital compression machine in accordance to [48] specifications.

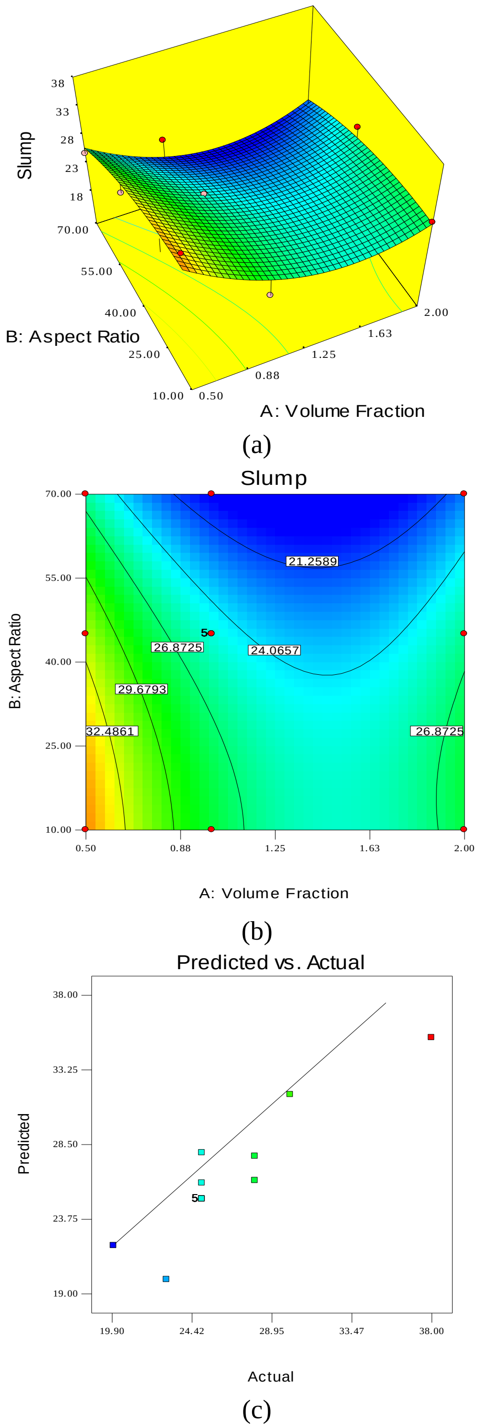
III. RESULTS AND DISCUSSIONS

The relationships between the factors and the responses, such as slump, 7 and 28 day compressive strength, were evaluated using Design Expert software. Model fitting was performed using regression techniques with a significance level of $\alpha = 0.05$.

A. *Workability (Slump) and Compressive Strengths*

The effect of each factor on the properties of ELTSFRC is plotted as 3-dimensional response surfaces and contour plots, as shown in Figures 1(a-b), 2(a-b), and 3(a-b). From the figures, the effect of each variable on the properties, such as slump, 7 and 28 day compressive strength can be observed. As shown in the response surface plot in Figure 1, workability decreases with an increase in both aspect ratio and volume fraction at all factor levels. This decrease is attributed to the high content and large surface area of the fibres, which absorb more cement paste to coat themselves. This increases the viscosity of the mixture, leading to slump loss [4].

Similarly, compressive strength increases with increases in aspect ratio, volume percentages, and curing periods of 7 and 28 days, as represented by the response surfaces and contour plots in Figures 2(a-b) and 3(a-b). However, beyond 1.0 % volume fraction and an aspect ratio of 70, a decreasing trend was observed compared to the control concrete at the same curing periods. The strength increment pattern in this research aligns with the findings of [49] and is also supported by [50].



(a)

(b)

(c)

Figure 1: Response surfaces of 3D (a), contour (b) showing factors effect on the Slump and parity plots (c).

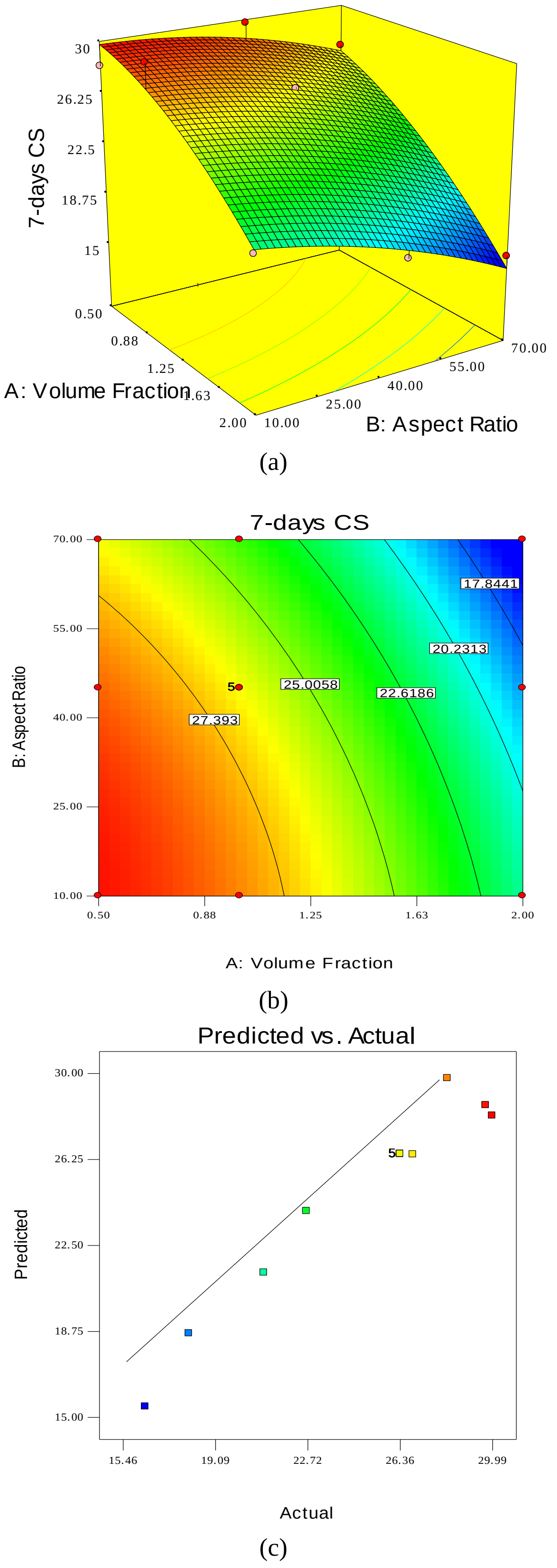


Figure 2: Response surfaces of 3D (a), contour (b) showing factors effect on the 7-days CS and parity plots (c).

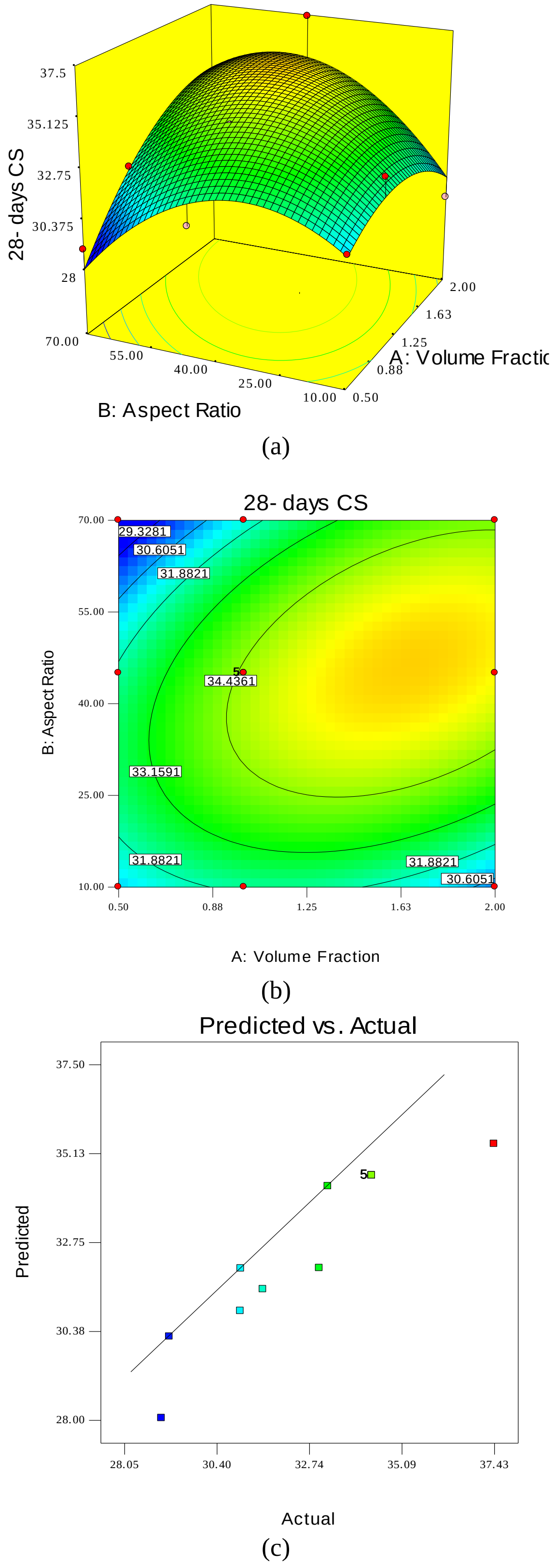


Figure 3: Response surfaces of 3D (a), contour (b) showing factors effect on the 28-days CS and parity plots (c).

B. Modelling the Properties of ELTSFRC

The model statistics summary for all the responses is presented in Table 8. Analysis of variance (ANOVA) provides key rational values such as the Fisher value (F-value), probability of significance (P-value), coefficient of determination (R^2), and adjusted coefficient of determination (Adjusted R^2), which determine the system's consistency. The table shows that all model F-values represent the ratio of regression mean square to mean square error. If the P-values are less than 0.05, the values indicate statistical significance at α=0.05. Additionally, the models' goodness of fit was further confirmed by the values of the coefficient of determination (R^2) and Adjusted R^2. The R^2 values should be close to the Adjusted R^2 values and near unity in each case for a good model, and the difference between R^2 and Adjusted R^2 should be within 0.2 [51], [52].

All models have an Adjusted R^2 within 0.2 of R^2, indicating they are good models. The models for slump and 7 and 28 day compressive strength can explain 79.44%, 90.09%, and 92.32% of the variability in the properties of ELSFRC, respectively. The strong correlation between experimental and predicted values, depicted as parity plots in Figures 1(c), 2(c), and 3(c), indicates the goodness of fit of the models. In all the figures, the plotted points are observed to cluster around the diagonal fit line.

TABLE 8: STATISTIC MODELS FOR ALL THE RESPONSES

Responses	R2	Adjust R2	P-value
Slump (mm)	0.8303	0.7090	0.0127
7-days CS (N/mm^2)	0.9525	0.9186	0.0002
28-days CS (N/mm^2)	0.8630	0.7622	0.0062

The signal to noise ratios for the three models—slump, 7 and 28-day compressive strength, from the Tables ANOVA are 9.838, 17.455, and 9.300, respectively. According to [53], a good RSM model should have a signal to noise ratio of at least 4. Since all the models have ratios greater than 4, they are suitable for describing the properties of ELTSFRC. The final model equations are presented as Equations 1, 2, and 3.

$$Y1\ (mm) = +24.19 - 2.88X1 - 3.73X2 + 0.89X1X2 + 5.43X1^2 - 1.83X2^2 \quad (1)$$

$$Y2\ (N/mm^2) = +25.37 - 4.87X1 - 2.29X2 - 0.63X1X2 - 1.34X1^2 - 0.78X2^2 \quad (2)$$

$$Y3\ (N/mm^2) = +35.29 - 1.38X1 + 0.29X2 + 1.72X1X2 - 1.55X1^2 - 2.88X2^2 \quad (3)$$

The relationship between the design factors and the responses (properties) of ELTSFC concrete was analysed and presented using 3D response plots, contour plots, and parity plots of RSM in Figures 1, 2, and 3. Figures 1(a-b) and 2(a-b) reveal a clear interaction effect between the factors volume fraction and aspect ratio on the properties of slump, and 7 and 28-day compressive strength. These properties increase with aspect ratio and volume fraction. This finding is consistent with the ANOVA results.

C. Numerical Optimisation

The response goal for slump was set in the range of 23 to 38 mm, satisfying the requirements for medium slump. However, the 7 and 28 day compressive strengths were maximized within the range of factor values studied, as shown in Table 7. The optimum mix of ELTSFRC is presented in Table 9, as shown in the Ramp plot in Figure 4.

Fibre reinforced concrete cuts construction time, labour costs, and reduces maintenance expenses, which is good news for contractors [54]. Even if these initial costs are high, applying fibre reinforcement might be economically feasible because of the saved maintenance expenditures. The construction industry has been associated with lowering waste, greenhouse gas emissions, resource conservation, and enhancing the durability and energy efficiency of the concrete structures by integrating end-of-life tyre fibres with steel-reinforced concrete. It is a holistic approach which can help offset the total impact from construction activities.

Although the application of RSM-optimized values for end-of-life steel fibre-reinforced concrete offers a sustainable and performance advantage, there are several challenges which must be addressed to realize this advantage in the real world. Overcoming material variability, ensuring consistent processing and quality, meeting regulatory standards, and gaining market acceptance are critical steps in successfully implementing this innovative approach in the construction industry. Convincing and seeking permission from various bodies, such as contractors, clients, and regulatory agencies, will be necessary when the optimized mix proportions, as derived by RSM, are to be introduced. Common difficulties in implementing for real construction work generally relate to opposition against the application of the RSM-optimized mix proportions and a lack of confidence [51].

TABLE 9: GOALS, LIMITS AND OPTIMIZATION VALUES

Response	Limits	Goals	Optimum Value
Volume Fraction	10 - 70	In Rage	33.86
Aspect Ratio (%)	0.5 – 1.2	In Range	1.01
Y1 (mm)	20 - 38	In Range	26.41
Y2 (N/mm^2)	16.34 – 29.74	Maximize	27.18
Y3 (N/mm^2)	29.00 – 37.43	Maximize	34.63

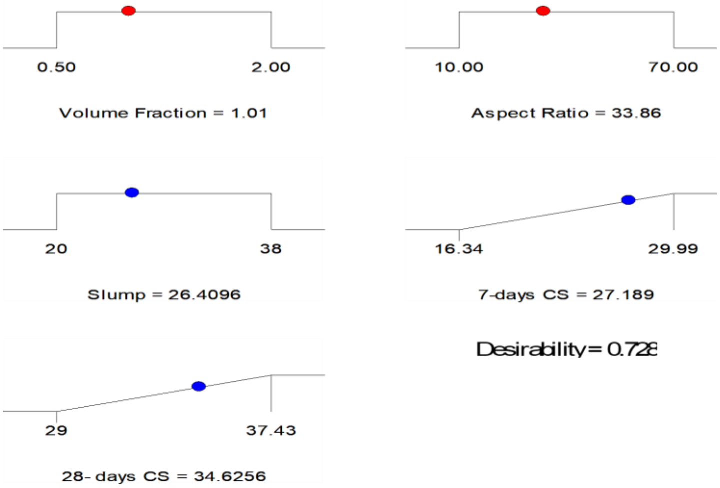


Figure: 4 Ramp plot

IV. CONCLUSION

In this study, RSM was utilized to model and optimize the effect of aspect ratio and volume fraction in ELTSFRC.

1. The impact of design factors on ELTSFRC properties has been evaluated. As the aspect ratio and volume fraction increase, the slump value decreases. Similarly, the compressive strength at 7 and 28 days increases up to an aspect ratio of 1.0% and a volume fraction of 45%. However, beyond these values, a slight decrease in compressive strength was observed at all curing ages.
2. The models for all the responses were statistically significant at the 95% confidence level, with all p-values being less than $\alpha = 0.05$.
3. The optimum response values were achieved by combining a 1.01% volume fraction and 33.86, resulting in a desirability of 0.73.

ACKNOWLEDGMENT

The authors would like to thank the Department of Civil Engineering, Faculty of Engineering and Engineering Technology, Abubakar Tafawa Balewa University, Bauchi, Nigeria for providing the experimental facilities and to all technical staff at Structural and Soil Engineering Laboratory.

REFERENCES

[1] Chukwuebuka, O., & Okonkwo, O. (2020). Financial leverage and dividend policy: Evidence from oil and gas firms in Nigeria. *Asian Journal of Economics, Business and Accounting*, *14*(2), 51-62.

[2] Yaman, S., Mohammed, A., & Elinwa, A. U. (2023). The The Effect of Aspect Ratio and Volume Fraction on Mechanical Properties of End of Life Tyre Steel Fibre Reinforced Concrete. *Journal of Civil Engineering Frontiers*, *4*(02), 27-33.

[3] The European Automobile Manufacturers' Association (ACEA), Worldmotorvehicleproduction2023.https://www.acea.auto/figure/world motorvehicleproduction/#:~:text=In%202022%2C%2085.4%20million %20motor,of%205.7%25%20compared%20to%202021.

[4] Chen, M., Si, H., Fan, X., Xuan, Y., & Zhang, M. (2022). Dynamic compressive behaviour of recycled tyres steel fibre reinforced concrete. Construction and Building Materials, 316, 125896.

[5] Grammelis, P., Margaritis, N., Dallas, P., Rakopoulos, D., & Mavrias, G. (2021). A review on management of end-of-life tyres (ELTs) and alternative uses of textile fibres. Energies, 14(3), 571.

[6] Mohajerani, A., Burnett, L., Smith, J. V., Markovski, S., Rodwell, G., Rahman, M. T., ... & Maghool, F. (2020). Recycling waste rubber tyres in construction materials and associated environmental considerations: A review. *Resources, Conservation and Recycling*, *155*, 104679

[7] The European Automobile Manufacturers' Association (ACEA), Worldmotorvehicleproduction2023.https://www.acea.auto/figure/world motorvehicleproduction/#:~:text=In%202022%2C%2085.4%20million %20motor,of%205.7%25%20compared%20to%202021. s), The TyGRe Project. Available: www.tygre.eu. Accessed: Feb. 3, 2024.

[8] Pilakoutas, K., Neocleous, K., & Tlemat, H. (2004, September). Reuse of tyres steel fibres as concrete reinforcement. In Proceedings of the Institution of Civil Engineers-Engineering Sustainability (Vol. 157, No. 3, pp. 131-138). Thomas Telford Ltd.

[9] Rowhani, A., & Rainey, T. J. (2016). Scrap tyres management pathways and their use as a fuel—a review. Energies, 9(11), 888.

[10] Ferdous, W., Manalo, A., Siddique, R., Mendis, P., Zhuge, Y., Wong, H. S., ... & Schubel, P. (2021). Recycling of landfill wastes (tyres, plastics and glass) in construction–A review on global waste generation, performance, application and future opportunities. Resources, Conservation and Recycling, 173, 105745.

[11] Banasiak, L., Chiaro, G., Palermo, A., & Granello, G. (2019). Recycling of end-of-life tyres in civil engineering applications: environmental implications.

[12] Tushar, Q., Santos, J., Zhang, G., Bhuiyan, M. A., & Giustozzi, F. (2022). Recycling waste vehicle tyres into crumb rubber and the transition to renewable energy sources: A comprehensive life cycle assessment. Journal of environmental management, 323, 116289.

[13] Tushar, Q., Santos, J., Zhang, G., Bhuiyan, M. A., & Giustozzi, F. (2022). Recycling waste vehicle tyres into crumb rubber and the transition to renewable energy sources: A comprehensive life cycle assessment. Journal of environmental management, 323, 116289.

[14] Antoniou, N., & Zabaniotou, A. (2013). Features of an efficient and environmentally attractive used tyres pyrolysis with energy and material recovery. Renewable and sustainable energy reviews, 20, 539-558.

[15] Li, X., Xu, H., Gao, Y., & Tao, Y. (2010). Comparison of end-of-life tire treatment technologies: A Chinese case study. Waste management, 30(11), 2235-2246.

[16] Williams, P. T. (2013). Pyrolysis of waste tyres: a review. Waste management, 33(8), 1714-1728.

[17] Ishola, F. A., Dunmade, I. S., Joseph, O. O., Okeniyi, J. O., & Akinlabi, E. T. (2024). Circular Economy Based Model for End-of-Life Tire Management in Emerging Economies. In Sustainable Engineering: Concepts and Practices (pp. 177-195). Cham: Springer International Publishing.

[18] Ali, A., Zafar, R., & Bibi, T. Comparative Effects of Chemical Pretreatments on Mechanical Properties of Sustainable Rubberized Concrete.

[19] Sarkawi, S. S., Aziz, A. A., & Kifli, A. (2017). Properties of graphene nano-filler reinforced epoxidized natural rubber composites. J Polym Sci Technol, 2(1), 36-44.

[20] Bijina, V., Jandas, P. J., Joseph, S., Gopu, J., Abhitha, K., & John, H. (2023). Recent trends in industrial and academic developments of green tyres technology. Polymer Bulletin, 80(8), 8215-8244.

[21] Claude, N. J. (2018). Effect of Recycled tyres Steel Fibres on Structural Performance and Impact Resistance of Rubberized Concrete (Doctoral dissertation, JKUAT).

[22] Trends, G. (2017). Challenges and opportunities in the implementation of the Sustainable Development Goals. United Nations Development Programme& United Nations Research Institute for Social Development.

[23] Bedewi, N. (2009). Steel fibre reinforced concrete made with fibres extracted from used tyres. Energy (Master's thesis in Civil Engineering), Addis Ababa University, Addis Ababa, Ethiopia.

[24] Köksal, F., Beycioğlu, A., & Dobiszewska, M. (2022). Optimization based on toughness and splitting tensile strength of steel-fiber-reinforced

concrete incorporating silica fume using response surface method. Materials, 15(18), 6218.

[25] La Rosa, A. D., Pergolizzi, E., Maragna, D., Recca, G., & Cicala, G. (2019). Reuse of carbon black from end-of-life tires in new pneumatic formulations and life-cycle assessment of the thermolysis process. Journal of Elastomers & Plastics, 51(7-8), 740-754.

[26] Munyi, J., Idowu, T., & Okumu, V. (2020). Performance assessment of bitumen when oil-based waste paint is used as an additive. *JOURNAL OF SUSTAINABLE RESEARCH IN ENGINEERING*, *6*(1), 1-10.

[27] Chalioris, C. E., Kosmidou, P. M. K., & Karayannis, C. G. (2019). Cyclic response of steel fiber reinforced concrete slender beams: An experimental study. *Materials*, *12*(9), 1398.

[28] Centonze, G., Leone, M., & Aiello, M. A. (2012). Steel fibres from waste tyres as reinforcement in concrete: A mechanical characterization Construction and Building Materials, 36, 46-57.

[29] Fall, D. (2014). *Steel Fibres in Reinforced Concrete Structures of Complex Shapes: Structural Behaviour and Design Perspectives*. Chalmers Tekniska Hogskola (Sweden).

[30] Khan, M., Cao, M., & Ali, M. (2018). Effect of basalt fibers on mechanical properties of calcium carbonate whisker-steel fiber reinforced concrete. *Construction and Building Materials*, *192*, 742-753.

[31] Mastali, M., & Dalvand, A. (2016). Use of silica fume and recycled steel fibres in self-compacting concrete (SCC). Construction and Building Materials, 125, 196-209.

[32] Yazıcı, Ş., İnan, G., & Tabak, V. (2007). Effect of aspect ratio and volume fraction of steel fibre on the mechanical properties of SFRC. Construction and Building Materials, 21(6), 1250-1253.

[33] Zhang, Y., & Gao, L. (2020). Influence of Tire‐Recycled Steel Fibers on Strength and Flexural Behavior of Reinforced Concrete. *Advances in Materials Science and Engineering*, *2020*(1), 6363105.

[34] Köksal, F., Şahin, Y., Gencel, O., & Yiğit, İ. (2013). Fracture energy-based optimisation of steel fibre reinforced concretes. Engineering Fracture Mechanics, 107, 29-37.

[35] Bayramov, F., Taşdemir, C., & Taşdemir, M. A. (2004). Optimisation of steel fibre reinforced concretes by means of statistical response surface method. Cement and concrete composites, 26(6), 665-675.

[36] Borror, C. M., Montgomery, D. C., & Myers, R. H. (2002). Evaluation of statistical designs for experiments involving noise variables. *Journal of Quality Technology*, *34*(1), 54-70.

[37] Akinoso, R., & Raji, A. O. (2011). Optimization of oil extraction from locust bean using response surface methodology. *European Journal of Lipid Science and Technology*, *113*(2), 245-252.

[38] Claudius, K., Baba, A. S., & Abubakar, A. (2023). Influence of Pulverized Animal Bone and Animal Bone Ash on the Mechanical Properties of Normal Strength Concrete using Response Surface Method. CONSTRUCTION, 3(1), 63-74.

[39] Abubakar, A., Idongesit, U. R., Konitufe, C., & Mohammed, A. (2020). Prediction of Strength Properties of Concrete Containing Calcined Black Cotton Soil Using Response Surface Methodology. *American Journal of Materials Synthesis and Processing*, *5*, 17.

[40] Baba, A. S., Umar, A. A., Abubakar, A., & Adagba, T. (2023). Application of Response Surface Methodology in Predicting and optimizing the properties of Concrete containing Ground Scoria and Metakaolin blended Cement in Concrete. Journal of Civil Engineering Frontiers, 4(01), 19-26.

[41] Konitufe, C., Baba, A. S., & Abubakar, A. (2023). Optimization of Calcined Termite-Mound Material (CTM) Mortar and Concrete using Response Surfaces Methodology. *Global Journal of Engineering and Technology Advances*, *14*(2), 047-060.

[42] Standard, B. (1995). 812-Part 2-Testing Aggregates–Part 2: Methods of Determination of Density. Standard. *British Standards Institution, London*.

[43] BS 812, (1995). Testing Aggregates – Part 2: Methods of Determination of Density. British Standard Specification. London.

[44] Standard, B. (1990). BS 812-110: 1990 testing aggregates-part 110: methods for determination of aggregate crushing value (ACV). *Bsi, Uk*.

[45] BS 812-112:, Testing aggregates: Methods for determination of aggregate impact value (AIV). London: British Standards Institution, 1990.

[46] Standard, A. C. I. (1996). Standard practice for selecting proportions for normal, heavyweight, and mass concrete. *ACI Man. Concr. Pract*, *1996*, 1-38.

[47] British Standard Institution. BS1881: (1983), Part 103. Method for Determination of Compacting factor. London, U.K.: British Standard institution.

[48] BS EN 12390 Part 3, Testing Hardened Concrete: Compressive Strength of Test Specimen. British Standard Specification. London, 2000.

[49] Ou, Y. C., Tsai, M. S., Liu, K. Y., & Chang, K. C. Compressive behavior of steel-fiber-reinforced concrete with a high reinforcing index. Journal of Materials in Civil Engineering, 24(2), 207-215, 2012.

[50] Dawood, E. T., & Ramli, M. Development of highstrengthflowablemortarwithhybrid fiber. Construction and Building Materials, 24(6), 1043-1050, 2010.

[51] Baba, A. S., Umar, A. A., Abubakar, A., & Adagba, T. (2023). Application of Response Surface Methodology in Predicting and optimizing the properties of Concrete containing Ground Scoria and Metakaolin blended Cement in Concrete. *Journal of Civil Engineering Frontiers*, *4*(01), 19-26.

[52] Dhakal, C. P. (2018). Multiple regression model fitted for rice production forecasting in Nepal: A case of time series data. *Nepalese Journal of Statistics*, *2*, 89-98.

[53] Cornell, J. A. (1987). *Response surfaces: designs and analyses*. Marcel Dekker, Inc..

[54] Plizzari, G., & Mindess, S. (2019). Fiber-reinforced concrete. In *Developments in the Formulation and Reinforcement of Concrete* (pp. 257-287). Woodhead Publishing.