

Predictive Analysis of Fly Ash, Ceramic Waste, and Construction Waste-Based Geopolymer Mortar Using Advanced Artificial Intelligence Algorithms

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Abstract—The growing harmful impacts on the environment are caused by fly ash from the coal industry, ceramic waste from the manufacturing industry, and construction and demolition waste from the construction sector. Alongside the notable CO₂ emissions associated with cement production, sustainable building practices have a serious challenge. This investigation presents a partial solution using fly ash as a binder, ceramic waste, and CDW as a fine aggregate, incorporating geopolymer activators like NaOH and Na₂SiO₃. Incorporating this geopolymer substance improves the strength of the materials while reducing their porosity. The study explores basic properties, including dry density, ultrasonic pulse velocity (UPV), rebound hammer strength, and compressive strength, with findings suggesting significant enhancements in strength throughout all mixes (N0 to N4) assigned to decreased porosity. Machine learning tools such as Response Surface Methodology (RSM) were utilized to predict the results, resulting in impressive R-squared values between 0.989 and 0.978. This investigation indicates that research into the future, materials based on geopolymer technology may completely substitute cement, providing sustainability and supporting waste recycling.

Index Terms—Geopolymers Mortar: NaOH, Na₂SiO₃, Fly ash, Ceramic Waste and CDW

I. INTRODUCTION

The construction sector finds significant challenges in incorporating sustainable development with the effectiveness of materials, significantly when reducing the ecological consequences of traditional building substances[1], [2], [3], [4]. The growing accumulation of fly ash, ceramic waste, and construction and demolition waste in landfills presents a significant environmental issue, leading to shortages of resources and pollution. Fly ash, a by-product of coal combustion has pozzolanic properties that improve material strength. Meanwhile, ceramic waste, frequently wasted during manufacturing and demolition, includes high silica content and outstanding mechanical characteristics[5], [6], [7]. Similarly, CDW, consisting of a combination of crushed concrete, bricks, and mortar, stands as a significant unused resource with the potential to serve as an alternative to natural aggregates. Although these materials are potentially used in construction applications, challenges remain in enhancing their properties to guarantee compatibility, structural performance, and sustainability[8], [9], [10], [11]. This investigation requires exploring the combined application of FA, CW, and CDW in developing constructed building materials, focussing on environmental issues and the demand for eco-friendliness.

On the other hand, the construction industry requires alternative materials because it has been discovered that natural materials, mainly when combined, generate higher CO₂ emissions during transportation. The combination of materials has significant effects on the environment. Various investigations suggest that FA is employed as a binder because of its chemical characteristics in ceramics and C&D waste as a fine aggregate. The application of CDW in the construction sector results in significant porosity. The composition of CDW results in considerable amounts of porosity.

Geopolymers: Chemicals, including NaOH and Na₂SiO₃, play a significant role in activating the C-S-H bonds found in FA. This activation dramatically improves mechanical properties of the material and decreases its porosity. Improving the connection development and concentration within the structure, these chemicals play a vital role in increasing the overall strength of mortar. Their application enhances fly ash-based mixtures' effectiveness within sustainable construction techniques[12], [13].

Another study indicates that alkali-activated mortar utilizes MSW incinerator bottom ashes and type C FA foundational materials. MIBA was processed using a ball mill can produce particles up to 45 µm in size. A 10 M NaOH solution and fluid Na₂SiO₃ were utilized as activators. The highest 28-day compressive strength was recorded for samples containing 20% MIBA and 80% FA, reaching approximately 53 MPa, while samples with 100% MIBA showed a strength of 10.6 MPa[14], [15], [16]. In addition to the evident pattern observed in the pore size distribution outcomes, along with porosity, compressive strength, and SEM analysis, the integration of 20% MIBA with FA was identified as the most favourable for application as a precursor in alkali-activated mortars.

This study focuses on porous reduction and implementing alternative building materials without compromising mechanical properties. This present research used FA, CW, and CDW, and the FA used alkaline actives such as NaOH and Na₂SO₃ to activate the C-S-H bond. The investigation evaluated workability and mechanical properties tests using ML techniques like RSM for optimization and prediction.

Based on the investigation, we achieved sustainability goals.

II. MATERIALS AND METHODS

2.1. Materials

2.1.1. Fly Ash (FA)

Fly ash, a by-product of coal combustion in heating facilities, is widely used as an extra binder in construction projects. The pozzolanic properties enable interaction with NaOH in water, forming additional C-S-H and enhancing cement-based materials' strength, as demonstrated in Table 1. FA improves workability, reduces the heat of hydration, and promotes environmental responsibility by minimizing the reliance on OPC. Guidelines such as ASTM C618 and IS 3812 specify the essential quality requirements, guaranteeing their successful application in mortar and a range of building supplies.

Table 1 Chemical Properties of between Cement and FA

Chemical Component	Cement (%)	Fly Ash (%)
SiO ₂	25	60
Al ₂ O ₃	8	30
CaO	63	8
Fe ₂ O ₃	5	8
MgO	4	2
SO ₃	2	1
K ₂ O	0.5	1
Na ₂ O	1	2
LOI	<3	<5

2.1.2. Ceramic and Construction Demolition Waste

The characteristics of CW, when gathered, displayed very sharp edges. Utilizing a ball milling machine for size reduction resulted in smooth edges, with the size of CW evaluating below 4.75 mm. In the same way for CDW, before utilizing the machine, a one-time hammer application was performed due to the large size being reduced to smaller dimensions, such as 10 mm to 6.4, 5, 4.8, and 4.75 mm. Subsequently, the machine was employed for further size reduction, focusing on dimensions below 4.75 mm. This analysis mentioned in Table 2 indicates the process of size reduction.

Table 2 Characteristics of CW and CDW

Property	CW	CDW
Specific Gravity	2.5	2.6
Bulk Density (kg/m ³)	1200	1300
Particle Size	Similar to fine sand (<4.75 mm)	Ranges from 0.075 mm to 4.75 mm
Shape	Angular, irregular	crushed, varies based on the source
Porosity (%)	CW < CDW	high
Surface Texture	Smooth	Rough

2.1.3. Sodium hydroxide (NaOH)

Sodium hydroxide was used as a primary alkaline activator in this research. It was sourced in pellet form with 98% purity and dissolved in distilled water to form an 8-molar solution. This strong alkali promotes the dissolution of aluminosilicate precursors, initiating the geopolymerization reaction. The solution was prepared 24 hours prior to mixing and stored in airtight containers to maintain consistency. Its role is critical in breaking down the raw materials and enabling the formation of binding gels.

2.1.4. Sodium silicate (Na₂SiO₃)

Sodium silicate solution was incorporated to complement the action of NaOH and enhance the reaction kinetics. The solution used contained approximately 26–28% silica (SiO₂) and 10–12% sodium oxide (Na₂O) by weight. This compound provides additional silicate ions necessary for forming a strong and dense geopolymer structure. When combined with NaOH, it significantly improves the mechanical performance and setting characteristics of the mixture. Proper handling and pre-mixing ensured uniform dispersion during the mixing phase.

2.1.5. Mix Combination

The mix design explores various combinations of cement, fly ash, normal aggregates, and ceramic and C&D waste aggregates to evaluate their performance in geopolymer mortar, as illustrated in Table 3. The amount of cement decreases from 500 g to 400 g, whereas the quantity of fly ash increases from 0 g to 100 g. This study substituted standard aggregates with ceramic and construction and demolition waste aggregates in increments of 100 g, culminating in 800 g. The quantities of sodium hydroxide and sodium silicate are consistently held at 57.14 g and 142.86 g, respectively, across all mixtures. This approach seeks to enhance material utilization while boosting strength and eco-friendliness.

Table 3 Mix Composition of this investigation

Mix Ratios	Binder		Aggregates			Sodium hydroxide	Sodium Silicate
	Cement	Fly ash	NFA	CW	CDW		
N	500	0	1000	0	0	57.14	142.86
N1	475	25	800	100	100	57.14	142.86
N2	450	50	600	200	200	57.14	142.86
N3	425	75	400	300	300	57.14	142.86
N4	400	100	200	400	400	57.14	142.86

2.2. Methods

2.2.1. Dry Density (DD)

The dry density technique for mortar conforms to the processes outlined in standards such as ASTM C642, customized for the specific needs of the region or project. The specified codes describe the procedures for drying the mortar sample, achieving a stable mass, and assessing the dry density by computing the dry mass's ratio to the specimen's volume.

2.2.2. Ultrasonic Pulse Velocity (UPV)

The Ultrasonic Pulse Velocity (UPV) method provides a non-invasive assessment of mortar quality. This approach examines the velocity of ultrasonic waves moving through the porous material, which is affected by its density characteristics. An elevated pulse velocity typically indicates improved quality, greater density, and superior uniformity, while a reduced velocity may suggest the existence of cracks, voids, or inferior material. The assessment follows recognized

standards such as IS 13311 (Part 1), ensuring an accurate material quality evaluation[17].

2.2.3. Rebound Hammer Strength

The Rebound Hammer Test is a non-destructive technique used to assess the compressive strength of mortar. This method involves utilizing a spring-driven steel hammer to impact the mortar surface, after which the rebound distance of the hammer is measured. The rebound value serves as an indicator of the surface hardness of mortar, which correlates with its compressive strength. The assessment is typically carried out following recognized standards like IS 13311 (Part 2), which provides the framework for testing equipment and interpreting the findings. This approach is commonly employed to guarantee quality and assess the durability of mortar[18].

2.2.4. Compressive Strength (CS)

The compressive strength test assesses a material's capacity to resist loads, typically on mortar samples such as cubes. Samples are prepared within established circumstances and evaluated with a universal testing machine, where force is incrementally applied until breakdown develops. The maximum load is calculated by dividing it Sectional region to establish the compressive strength in MPa. The results are significantly influenced by factors such as curing

duration, mix proportions, and adding additives like fibers or pozzolans. This approach offers a crucial comprehension of building materials' mechanical behavior and existence[19].

III. RESULTS AND DISCUSSION

3.1. Dry Density (DD)

Deploying alternative materials such as FA and recycling fine aggregates in the construction sector has produced remarkable outcomes. This investigation employed various mixed designs, including N, N1, N2, N3, and N4, with curing durations of 14 and 28 days. The conventional mortar cube exhibits 7 days DD results of 620.34, 637.1, 651.21, 645, and 631, respectively. As a result, the density of curing time was enhanced due to the FA, having finely arranged particles that contribute to the porous structure. After 28 days of DD, the results demonstrated remarkable values related to the curing duration. In that order, 632.58, 642.84, 651.21, 650.49, and 640.91 are shown in Figure 1. The DD values decreased afterward the N2 mix ratio as caused by the increased use of recycled aggregate materials; the CDW demonstrates a highly porous structure. The FA promotes maximum N2 mix ratios to reduce porosity and improve DD. The polynomial equation $y = -5.8457x^2 + 37.996x + 587.24$ and the correlation value of $R^2 = 0.973$ indicate a strong relationship between the variables.

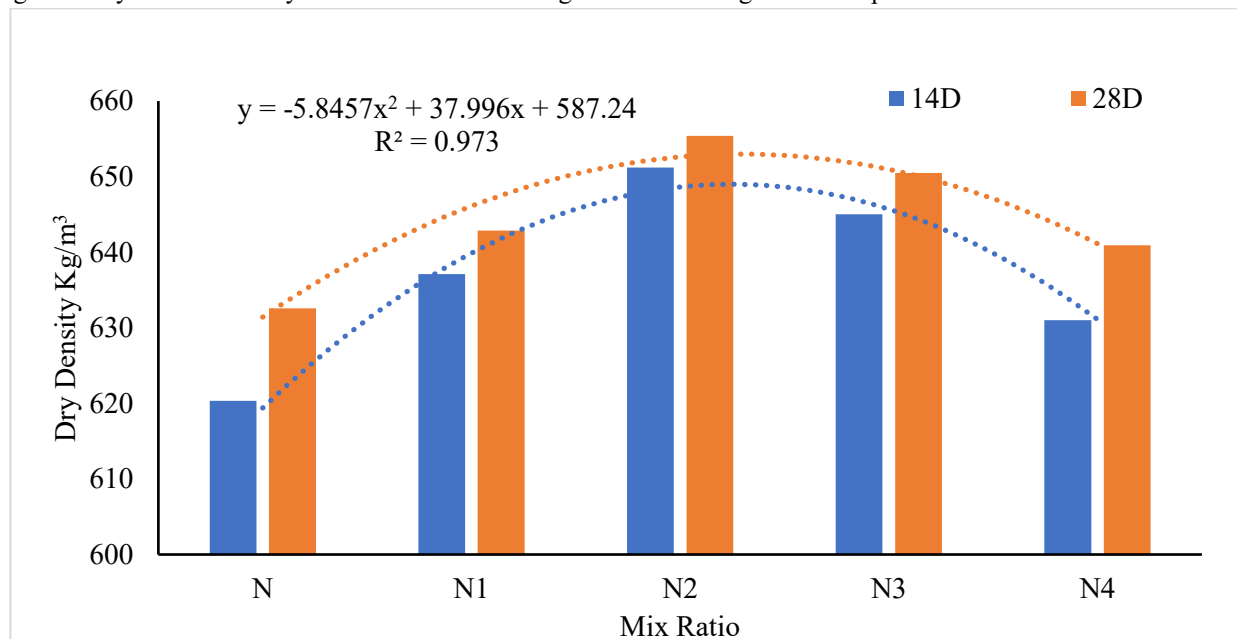


Figure 1 Dry Density Results

3.2. Ultrasonic Pulse Velocity (UPV)

The mortar cube was tested with UPV to evaluate its porosity; this investigation demonstrated that throughout the curing period, the porosity notably decreased with the incorporation of FA, CW, and CDW. This study assessed tests conducted at 14 and 28 days, showing that DD influences the UPV values shown in Figure 2. The relationship between density and UPV value is characterized by a direct proportionality, indicating that the UPV value also rises significantly as density increases. From this, two

methods reveal whether compressive strength is enhanced or reduced. Over fourteen days, the results were 42, 45.6, 50.4, 51.52, and 44.7. After extending the duration to 28 days, the outcomes showed improvement with values of 43.6, 47.96, 53.94, and 46.38. The polynomial equation $y = -1.5214x^2 + 9.9386x + 33.12$ and the correlation value of $R^2 = 0.9212$ suggests a robust connection between the variables.

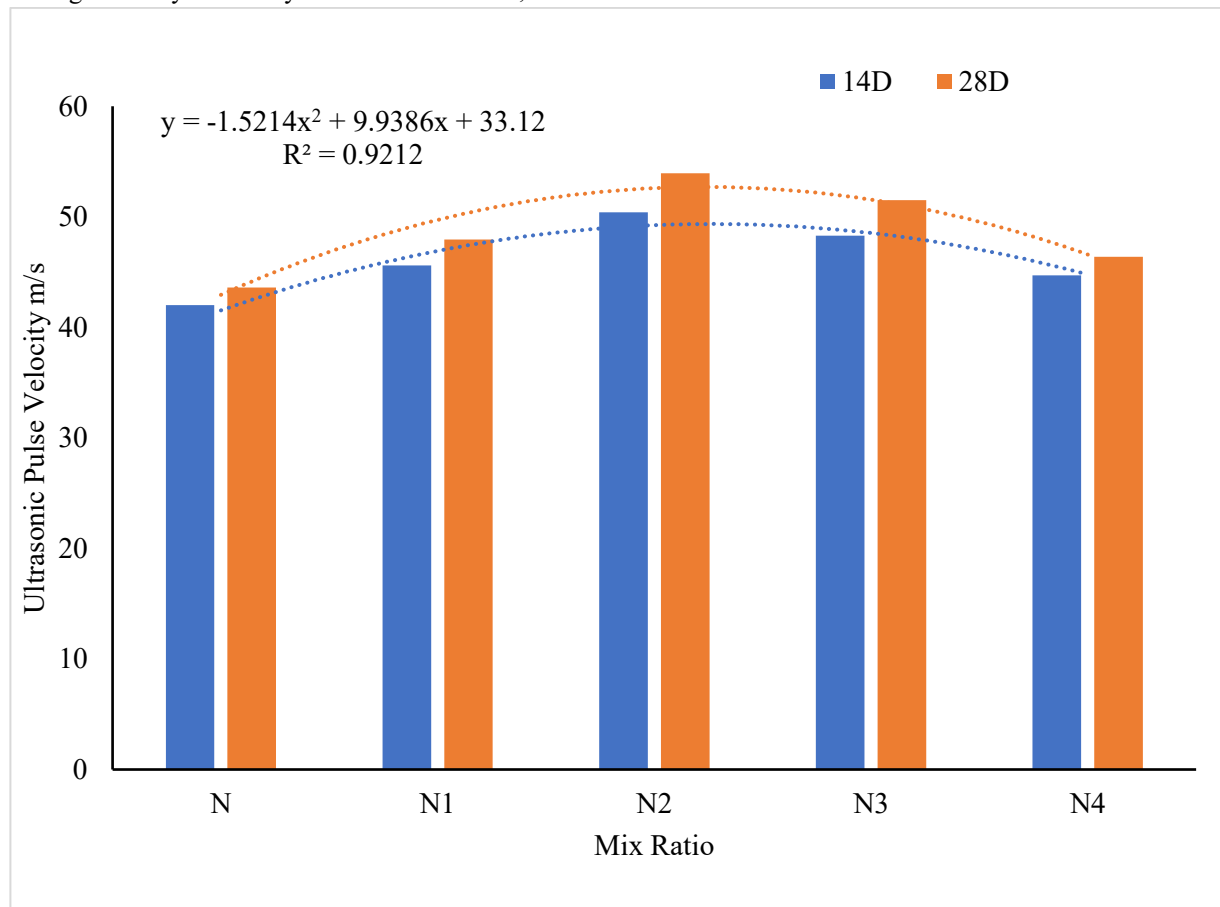


Figure 2 Ultrasonic Pulse Velocity Outcomes of The Cube

3.3. Rebound Hammer Strength

The RBH method seems like compressive strength but is a non-destructive test. The position of the mortar cube's outer surface improved its strength. The current investigation employed a 70 * 70 mm cube, choosing one side surface position of the cube, and established a grid comprising 9 points for each position investigated. Every evaluation demonstrates remarkable strength metrics. Following more than 14

days, the recorded strengths were 26.8, 28.4, 32.5, 30.6, and 29.1, respectively. Upon comparing the strengths at 28 days to those from previously, there was an improvement to 28.64, 30.5, 34.91, 32.56, and 30.7, respectively, as indicated in Figure 3. The polynomial equation $y = -0.8714x^2 + 5.9086x + 21.34$ and the correlation value of $R^2 = 0.8085$ indicate a strong relationship between the variables.

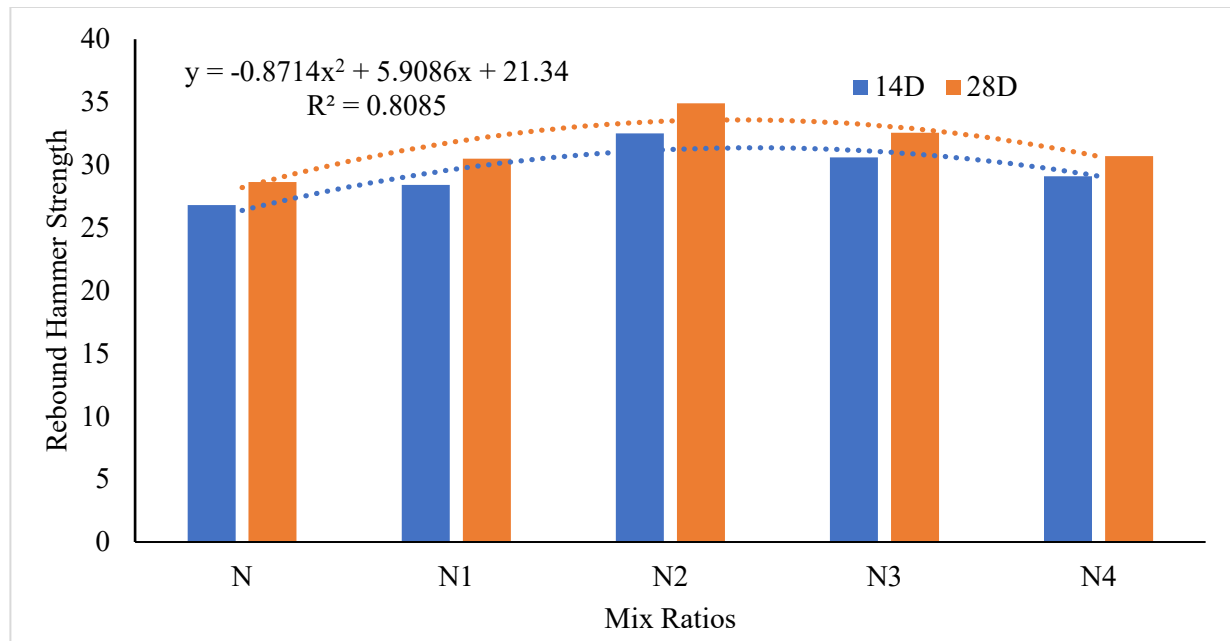


Figure 3 Rebound Hammer Strength Values of Cube

3.4. Compressive Strength (CS)

Incorporating alternative materials led to a notable increase in compressive strength, reaching N2 while maintaining overall strength levels. However, incorporating additional recycling materials suggests a decrease in strength due to greater quantity of materials within the porous structure. Figure 4 shows the normal porous of a cube; it means that in a standard cube when adding recycled materials, the porous reduced and raised more recycled aggregates, which

increased the porous and decreased the compressive strength. The results over the 14 days are as follows: 30.268, 32.638, 35.884, 34.619, and 31.728, respectively. After 28 days, the findings were 33.519, 36.826, 39.443, 38.376, and 34.582, respectively. The polynomial equation $y = -1.0738x^2 + 6.9328x + 24.041$, along with the correlation value of $R^2 = 0.9204$ shown in Figure 5, suggests an effective relationship between the variables.

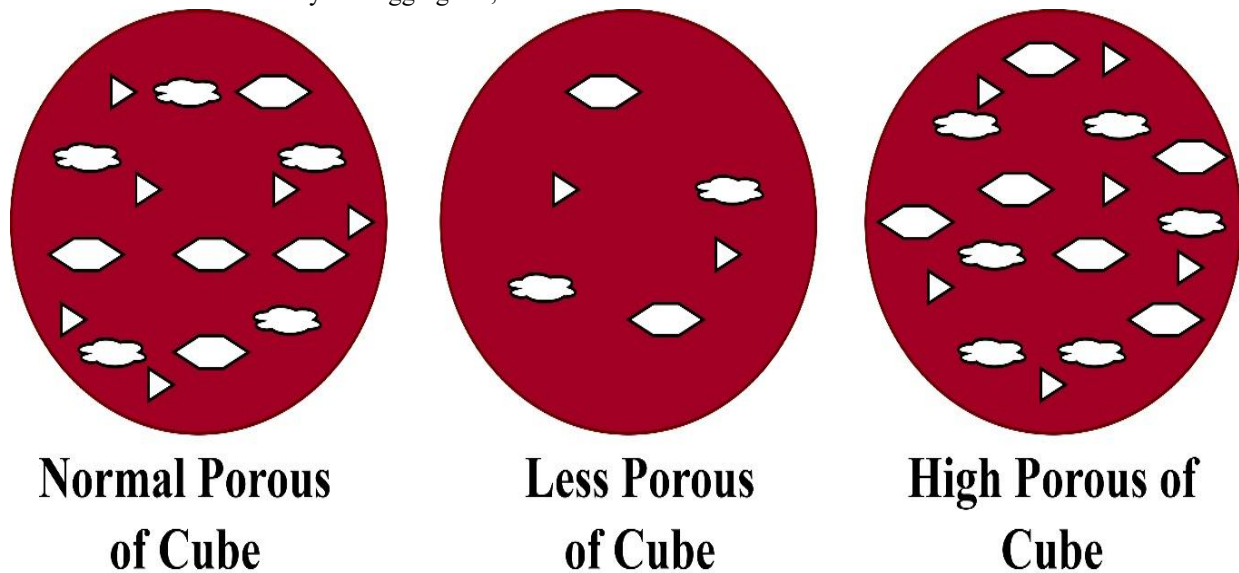


Figure 4 Porous of The Cube

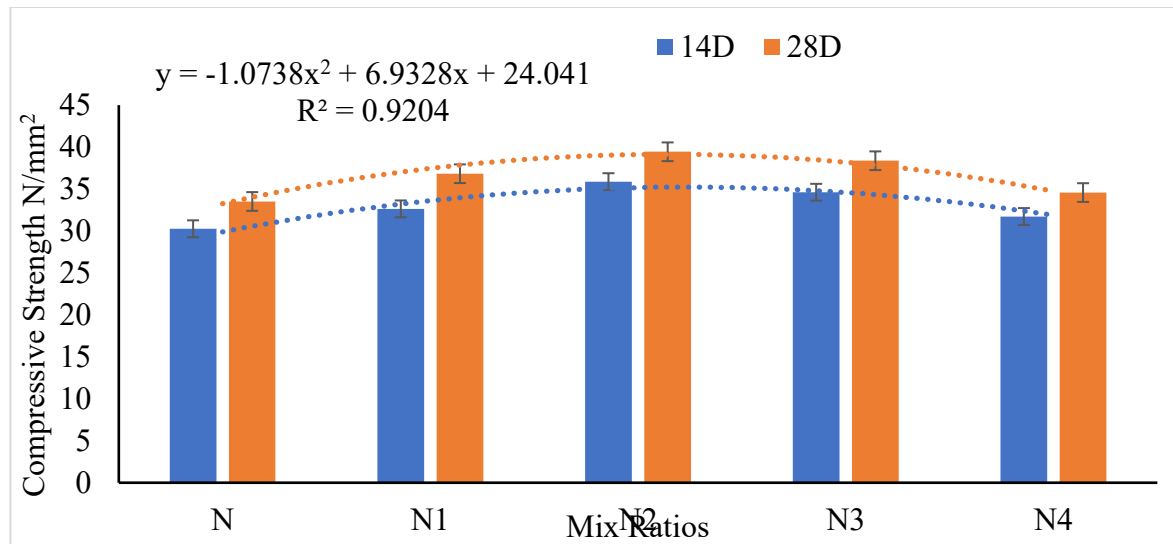


Figure 5 Compressive Strength of Results

IV. ANALYSING WITH RSM FOR OPTIMIZATION AND PREDICTION

13.0.5.0; this analysis primarily employed a quadratic model for each variable. Table 4 presents the software specifications and the procedure to generate plots.

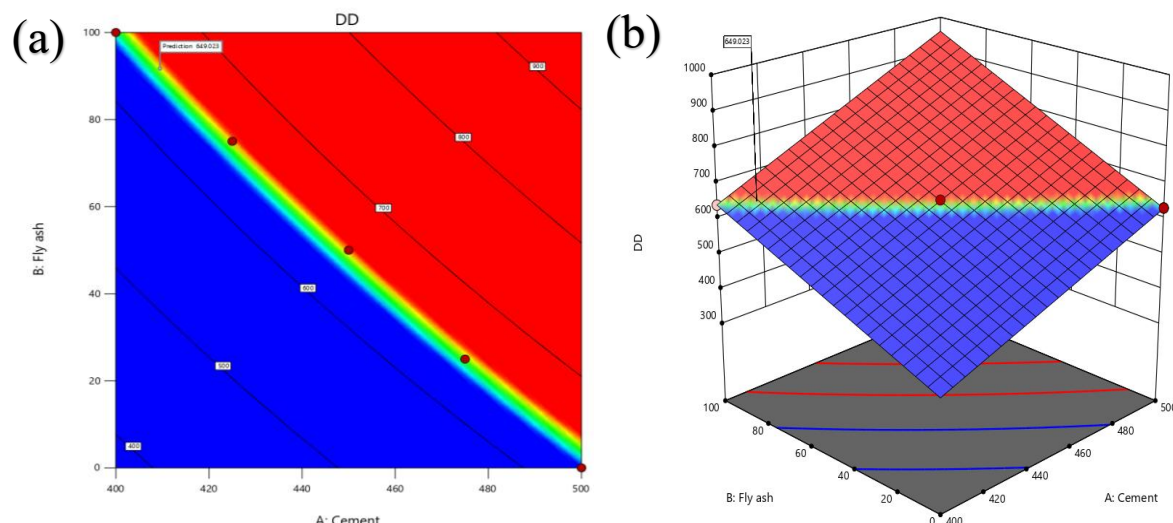
This application of machine learning is utilized in the development of export software. The version is

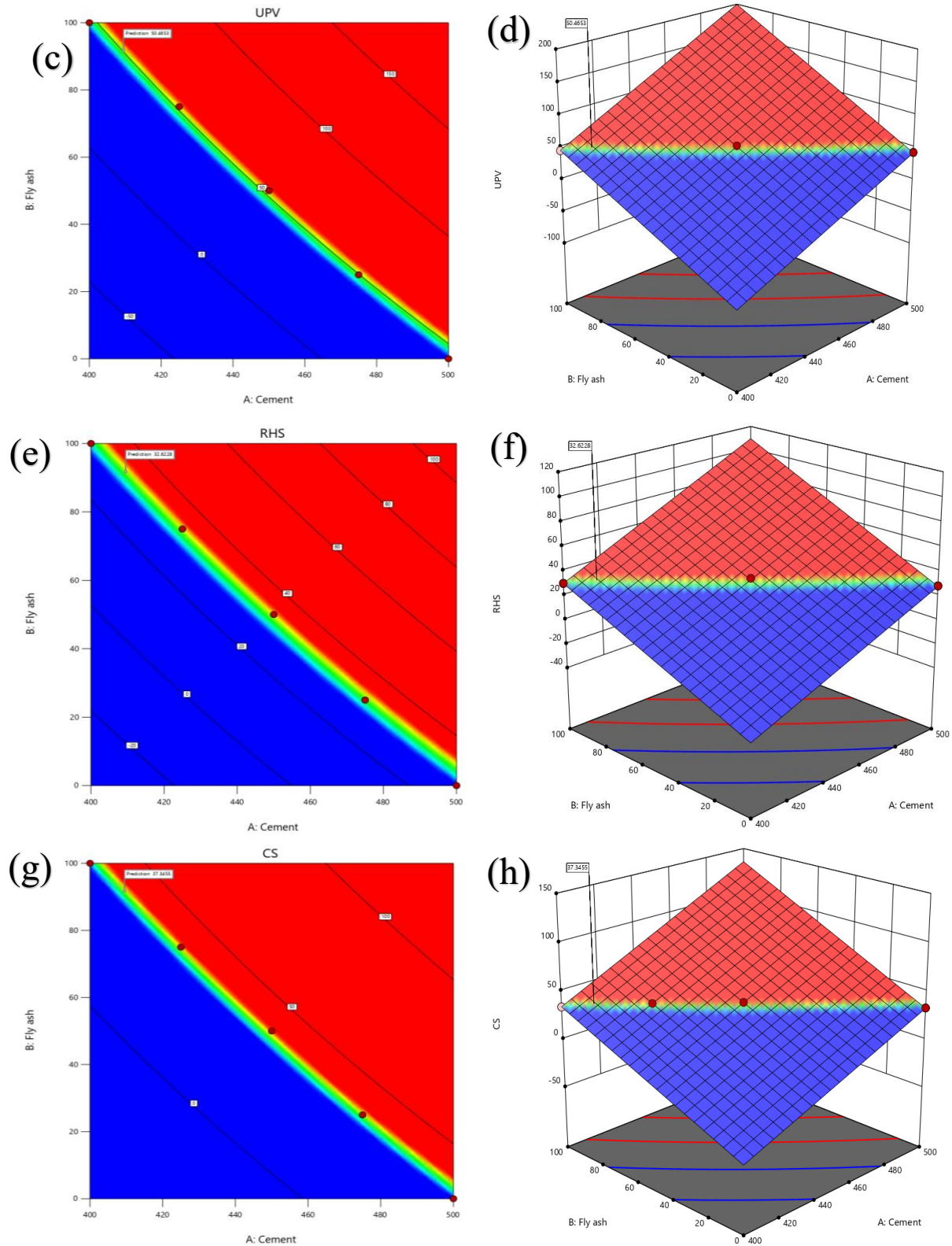
Table 4 RSM Detail Version

File Version	13.0.5.0		
Study Type	Response Surface	Subtype	Randomized
Design Type	Blank Spreadsheet	Runs	5.00
Design Model	Quadratic	Blocks	No Blocks

This investigation employed advanced machine learning methods such as RSM for enhancement and projections. The findings demonstrated remarkable abilities to predict and evaluate contour and three-dimensional surface visualizations. The representation

presented in Figure 6 (a), (b) demonstrates DD, (c), (d) shows UPV, (e), (f) illustrates an RBH, and (g) (h) represents CS. All these plots illustrate improved capabilities when employing alternative materials in the construction sector.





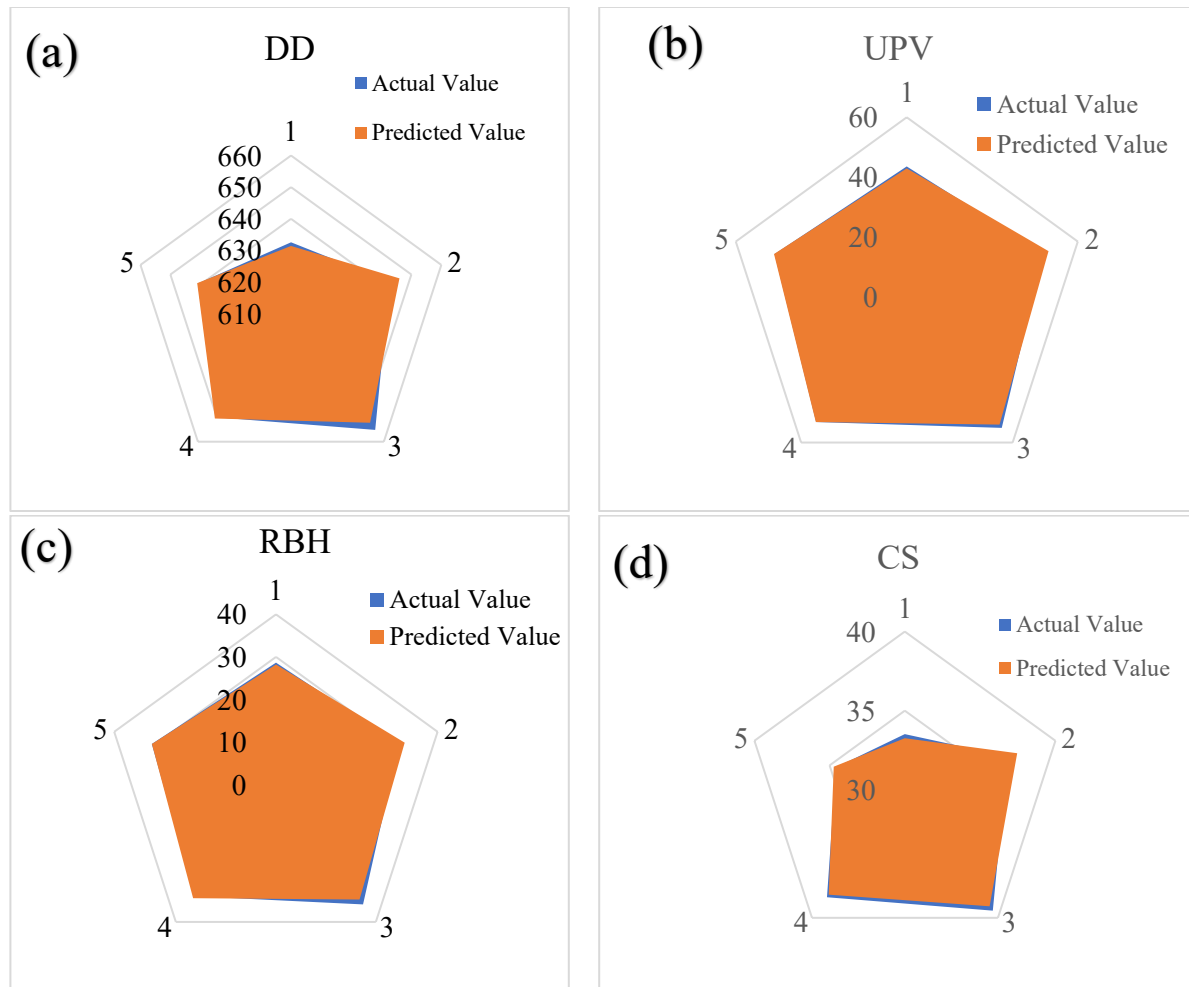


Figure 7 Indicates (a) DD, (b) UPV, (c) RBH, and (d) CS

V. CONCLUSION

In conclusion, this study shows that waste materials such as FA, CW, and CDW are used in the construction industry. FA was used as a substitute for cement, while CW and CDW were used as fine aggregates. Furthermore, NaOH and Na₂SiO₃ were added to produce the active C-S-H bond. Using waste materials not only reduces landing fills but also achieves sustainability.

- Utilizing FA 50g, CW, and CDW 200g resulted in an enhancement of the porous structure of the CDW while also decreasing the porosity of the mortar cube.
- The UPV values demonstrate a reduction in the porosity of the mortar cube, which is attributed to the addition of fly ash.

- The RBH results were significant when utilizing the N2 mix design for 14 and 28 days of curing time.
- Compressive strength highlighted N2 results for 14 and 28 days at 35.884 and 39.443, respectively.
- This investigation employed advanced machine learning techniques, including RSM, to establish predictions.
- These ML prediction values demonstrate an impressive position compared to the experimental values.

In the future, this study suggests that utilizing more FA will increase strength, which is attributed to the optimal particle size. In the construction sector, the application of machine learning for optimization and prediction is limited when testing samples to find results.

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Consent for publication: Not applicable.

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Financial interests: The authors declare they have no financial interests.

Data availability: The datasets used and/or analyses during the current study are available from the corresponding author on reasonable request.

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