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Utilization of Cow Dung Ash and Eggshell Powder as Partial Cement Replacement in Concrete

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***Abstract* - The production of cement is associated with significant carbon dioxide emissions, necessitating the development of sustainable alternatives in concrete technology. This study investigates the utilization of cow dung ash (CDA) and eggshell powder (ESP) as partial replacements for ordinary Portland cement (OPC) in concrete. Experimental investigations were conducted on M20 grade concrete by incorporating CDA (2.5–10%) and ESP (2.5–7.5%) in both binary and ternary combinations. The performance of the modified concrete was evaluated in terms of workability, compressive strength, and microstructural characteristics using X-ray diffraction (XRD) analysis. In addition, an artificial neural network (ANN) model was developed to predict compressive strength based on mix composition. The results indicate that workability increases with CDA content, while ESP exhibits a dosage-dependent influence. The optimum performance was achieved for the ternary mix containing 2.5% CDA and 5% ESP, which exhibited higher compressive strength compared to the control mix. XRD analysis confirmed enhanced formation of calcium silicate hydrate (C–S–H) gel and reduced portlandite content, indicating improved microstructural densification. The ANN model demonstrated high prediction accuracy with a strong correlation between experimental and predicted results. The findings suggest that CDA and ESP can be effectively utilized as sustainable supplementary cementitious materials, contributing to improved concrete performance and reduced environmental impact.**

***Keywords:* Cow dung ash, Eggshell powder, Sustainable concrete, Cement replacement, Compressive strength, X-ray diffraction (XRD), Artificial neural network (ANN), Pozzolanic materials, Microstructural analysis**

I. INTRODUCTION

The rapid growth of the construction industry has significantly increased the demand for cement, a key component of concrete. However, cement production is energy-intensive and contributes substantially to global carbon dioxide (CO_2) emissions, accounting for approximately 7–8% of total anthropogenic emissions (International Energy Agency [IEA], 2022). This environmental burden has prompted the need for sustainable alternatives that can reduce cement consumption without compromising the performance of concrete.

One of the most effective approaches to addressing this challenge is the incorporation of supplementary cementitious materials (SCMs), which partially replace cement while maintaining mechanical performance and improving sustainability. While conventional SCMs such as fly ash and silica fume have been widely used, their availability is increasingly constrained by industrial dependency and regional limitations (Mehta & Monteiro, 2014). Consequently, recent research has focused on alternative waste-derived materials that are locally available, cost-effective, and environmentally beneficial (Amin et al., 2022; Wang et al., 2023).

Among such materials, cow dung ash (CDA) and eggshell powder (ESP) have emerged as promising candidates for sustainable concrete production. These materials are abundantly available as agricultural and food waste, offering potential benefits in waste management and resource conservation. Their incorporation in concrete has been associated with changes in both fresh and hardened properties, depending on the replacement level and material characteristics (Worku et al., 2023; Chen et al., 2022).

Recent studies have also explored the use of multiple waste materials in combination to improve concrete performance. Such approaches aim to utilize complementary material characteristics to achieve enhanced properties. However, despite growing interest, limited research has systematically investigated the combined use of CDA and ESP in concrete, particularly with respect to their microstructural behavior and predictive modeling.

In addition, the application of advanced techniques such as artificial neural networks (ANN) for predicting the behavior of such systems remains limited. Machine learning approaches have shown strong potential in modeling concrete properties, but their use in conjunction with unconventional waste materials is still emerging (Zhang et al., 2024; Zhu et al., 2024).

In this context, the present study aims to investigate the combined use of CDA and ESP as partial replacements for cement in concrete. The study evaluates their influence on workability and compressive strength, examines microstructural characteristics using X-ray diffraction (XRD), and develops an ANN model for strength prediction. The objective is to identify an optimal replacement combination and provide insight into the factors governing performance enhancement.

II. REVIEW OF LITERATURE

Previous research on waste-derived supplementary cementitious materials has demonstrated that the performance of concrete is highly dependent on the type, proportion, and interaction of replacement materials with cement hydration processes. The incorporation of bio-waste materials has been shown to enhance sustainability while influencing mechanical and durability properties (Amin et al., 2022; Wang et al., 2023).

Studies focusing on cow dung ash (CDA) indicate that its influence on concrete is governed primarily by its pozzolanic characteristics and physical properties. CDA contains reactive silica, which participates in secondary hydration reactions with calcium hydroxide (CH) to form additional calcium silicate hydrate (C–S–H) gel. However, increasing CDA content has been associated with reduced density and compressive strength due to dilution effects and increased water demand (Rath & Madhav Rao, 2023). Additionally, CDA has been reported to act as a retarding agent, increasing setting time and affecting workability (Kamat et al., 2021). Experimental studies confirm that optimal performance is achieved only within a limited replacement range (Worku et al., 2023).

In contrast, eggshell powder (ESP) primarily influences concrete through its high calcium content and filler effect. ESP, largely composed of calcium carbonate, enhances hydration by increasing the availability of calcium ions and improving particle packing. This leads to refinement of the microstructure and increased matrix density (Chen et al., 2022). The use of calcined ESP has been shown to accelerate hydration reactions and improve early-age strength, although excessive replacement results in strength reduction due to decreased effective binder content (Khalid et al., 2023). Furthermore, the fine particle size of ESP increases surface area, which can adversely affect workability (Teara & Ing, 2020).

The combined use of silica-rich and calcium-rich materials has been reported to produce synergistic effects in concrete systems. The interaction between these materials enhances hydration kinetics and promotes the formation of additional C–S–H gel, leading to improved mechanical performance (Rasid et al., 2022). Similar findings have been reported in studies involving ash-based materials combined with ESP, where improvements in compressive, tensile, and flexural strength were observed up to an optimal replacement level (Deshpande et al., 2018). However, beyond this level, strength decreases due to incomplete reactions and reduced binder efficiency.

Despite these advancements, most studies have focused on CDA and ESP either independently or in combination with conventional SCMs. A systematic investigation of their direct interaction as a binary–ternary system remains limited, particularly in terms of microstructural validation. Moreover, the integration of experimental results with predictive modeling techniques is rarely addressed.

Recent advancements in artificial neural networks (ANN) have demonstrated their capability in modeling nonlinear relationships in concrete systems. ANN models have been successfully applied to predict compressive strength based on mix parameters with high accuracy (Zhang et al., 2024; Zhu et al., 2024). In addition, ANN-based approaches have shown promising results in predicting the behavior of eggshell-based concrete systems (Paruthi et al., 2023). However, their application to systems incorporating CDA and ESP remains largely unexplored.

Therefore, there is a clear need for a comprehensive study that integrates experimental investigation, microstructural analysis, and predictive modeling to evaluate the combined performance of CDA and ESP in concrete. The present study addresses this gap by systematically examining their synergistic effects and developing an ANN-based predictive framework.

III.RESEARCH OBJECTIVES

The objectives of the present study are as follows:

- To evaluate the suitability of cow dung ash (CDA) and eggshell powder (ESP) as partial replacements for cement by examining their chemical characteristics and influence on concrete properties.
- To investigate the effects of CDA and ESP on the workability and compressive strength of concrete and to determine the optimum replacement levels.
- To analyze the microstructural characteristics and hydration products of hardened concrete using X-ray diffraction (XRD).
- To develop and validate an artificial neural network (ANN) model for predicting compressive strength and to assess its accuracy by comparing predicted and experimental results.
- To assess the potential of CDA and ESP in producing sustainable, cost-effective, and eco-friendly concrete.

IV.MATERIALS AND METHODS

4.1 Experimental Design Strategy

The experimental program was designed to evaluate the individual and combined effects of cow dung ash (CDA) and eggshell powder (ESP) as partial replacements for ordinary Portland cement (OPC) in concrete. A control mix was first established, followed by a series of binary and ternary mixes incorporating varying proportions of CDA and ESP.

The selected replacement levels were based on previous studies to capture both optimal and limiting performance conditions. To ensure consistency and isolate the influence of replacement materials, all mixes were prepared with a constant water–cement ratio of 0.45 and identical aggregate proportions.

4.2 Materials

Ordinary Portland cement (OPC) conforming to IS 456:2000 was used as the primary binder. Fine aggregates consisted of natural river sand, and crushed coarse aggregates of suitable grading were used. Potable water was used for mixing and curing, and a superplasticizer (Conplast SP430) was added to maintain workability.

Cow dung ash (CDA) was produced by collecting cow dung from local sources, followed by air drying and controlled combustion at approximately 200°C. The ash was then cooled, ground, and sieved through a 90 µm sieve. Eggshell powder (ESP) was obtained from waste eggshells, which were cleaned, dried, and ground into fine powder, followed by sieving through a 90 µm sieve.

The physical and chemical properties of the materials were determined using standard testing procedures, and the results are presented in Table 1.

Table 1. Physical and Chemical Properties of Materials
(a) Physical Properties

Material	Specific Gravity	Fineness (%) / Modulus	Water Absorption (%)	Color
Cement (OPC)	3.15	5%	—	Grey
Fine Aggregate	2.65	2.83 (FM)	1.10	—
Coarse Aggregate	2.74	5.20 (FM)	0.50	—
Cow Dung Ash (CDA)	2.16	5%	—	Black

Eggshell Powder (ESP)	0.84	5%		—	White

(b) Chemical Composition (XRF Analysis)

Oxide Composition	OPC (%)	CDA (%)	ESP (%)
SiO_2	62.00	21.41	1.11
Al_2O_3	22.00	1.31	0.20
Fe_2O_3	1.10	2.63	0.16
CaO	4.20	4.01	49.52
MgO	0.80	1.88	0.92

Source: XRF analysis conducted at Ulogam Analytical Services, Chennai.

4.3 Mix Proportions

The mix proportions adopted for M20 grade concrete incorporating cow dung ash (CDA) and eggshell powder (ESP) as partial replacements for cement are presented in Table 2. A control mix (M_0) was prepared without any replacement, while binary mixes were developed by replacing cement with CDA and ESP individually at varying percentages. Ternary mixes were formulated by combining CDA and ESP to evaluate their synergistic effect on concrete performance. The total binder content, water content, and superplasticizer dosage were maintained constant across all mixes to ensure consistency and enable a direct comparison of results in Table 2.

Table 2. Mix Proportions of Concrete with CDA and ESP (per m³)

Mix ID	OPC (kg/m³)	CDA (kg/m³)	ESP (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Water (kg/m³)	Superplasticizer (kg/m³)
M_0	359.26	0	0	1210.58	687.60	161.60	2.80
M_1	350.20	8.90	0	1226.90	696.90	161.60	2.80
M_2	341.30	17.90	0	1225.40	696.00	161.60	2.80
M_3	332.30	26.90	0	1224.00	695.20	161.60	2.80
M_4	323.30	35.90	0	1220.90	693.50	161.60	2.80
M_5	350.28	0	8.98	1215.53	725.57	161.60	2.80
M_6	341.30	0	17.90	1203.10	683.30	161.60	2.80
M_7	332.30	0	26.90	1189.60	675.70	161.60	2.80
M_8	341.30	8.98	8.98	1213.51	689.29	161.60	2.80
M_9	332.32	8.98	17.96	1201.43	682.42	161.60	2.80
M_{10}	323.34	8.98	26.94	1220.90	693.50	161.60	2.80

4.4 Specimen Preparation and Curing

Concrete mixing was carried out to ensure uniform distribution of materials. Fresh concrete was cast into cube moulds of size 150 mm × 150 mm × 150 mm. For each mix, three specimens were prepared. After 24 hours of casting, the specimens were demoulded and cured in water under standard laboratory conditions until testing at 7 and 28 days.

4.5 Testing Procedures

4.5.1 Workability Test

Workability was evaluated using the slump cone test in accordance with standard procedures. The slump value was recorded as a measure of consistency.

4.5.2 Compressive Strength Test

Compressive strength tests were conducted as per IS 516:1959 using a compression testing machine. The average of three specimens was reported for each mix.

4.6 Microstructural Analysis (XRD)

X-ray diffraction (XRD) analysis was performed to identify the crystalline phases present in hardened concrete. Powdered samples were prepared by crushing and sieving to a particle size below 90 µm.

The samples were analyzed over a scanning range of 10°–80° (2θ) using monochromatic X-ray radiation. The obtained diffraction patterns were interpreted using standard databases to identify hydration products such as calcium silicate hydrate (C–S–H), portlandite (CH), alite, belite, quartz, and ettringite.

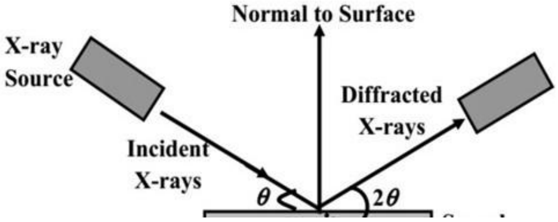


Figure 1. Schematic representation of X-ray diffraction (XRD) principle based on Bragg’s law.

4.7 Artificial Neural Network (ANN) Modeling

An artificial neural network (ANN) model was developed to predict compressive strength based on input parameters such as mix proportions and curing age. The model consisted of an input layer, a hidden layer, and an output layer, forming a feed-forward network.

The model was trained using the Levenberg–Marquardt backpropagation algorithm. Experimental data were divided into training, validation, and testing sets. Model performance was evaluated using the coefficient of determination (R^2) and root mean square error (RMSE).

4.8 Statistical Considerations

All experimental results were obtained as the average of three specimens. The variation between specimens was within acceptable limits. The ANN predictions were compared with experimental values to evaluate model accuracy.

V. RESULTS

5.1 Workability of Concrete

The workability of concrete mixes incorporating cow dung ash (CDA) and eggshell powder (ESP) was evaluated using the slump cone test. The measured slump values for all mixes are presented in Table 3.

Table 3. Slump Values of Concrete Mixes

Mix ID	CDA (%)	ESP (%)	Slump (mm)
M_0	0	0	95
M_1	2.5	0	98
M_2	5	0	105
M_3	7.5	0	107
M_4	10	0	110
M_5	0	2.5	90
M_6	0	5	95
M_7	0	7.5	105
M_8	2.5	2.5	105
M_9	2.5	5	106
M_{10}	2.5	7.5	108

Table 3 presents the workability of concrete mixes incorporating varying proportions of cow dung ash (CDA) and eggshell powder (ESP), measured using the slump cone test. The control mix (M_0) exhibited a slump value of 95 mm, indicating medium workability suitable for conventional concrete applications. An increasing trend in slump was observed with higher CDA replacement levels (M_1–M_4), where the slump value increased from 98 mm to 110 mm. This behavior can be attributed to the relatively lower specific gravity and porous nature of CDA, which enhances internal lubrication and reduces inter-particle friction within the mix.

In contrast, the incorporation of ESP resulted in an initial reduction in slump (M_5: 90 mm), likely due to its finer particle size and higher surface area, which increases water demand. However, with further increase in ESP content (M_6–M_7), the slump values improved, suggesting better particle packing and dispersion effects at moderate replacement levels. The ternary mixes (M_8–M_{10}) exhibited relatively consistent and higher slump values ranging from 105 mm to 108 mm, indicating improved cohesion and uniformity. This suggests that the combined use of CDA and ESP contributes to balanced rheological behavior. All mixes exhibited a true slump without visible segregation or bleeding, indicating adequate cohesiveness and suitability for practical applications.

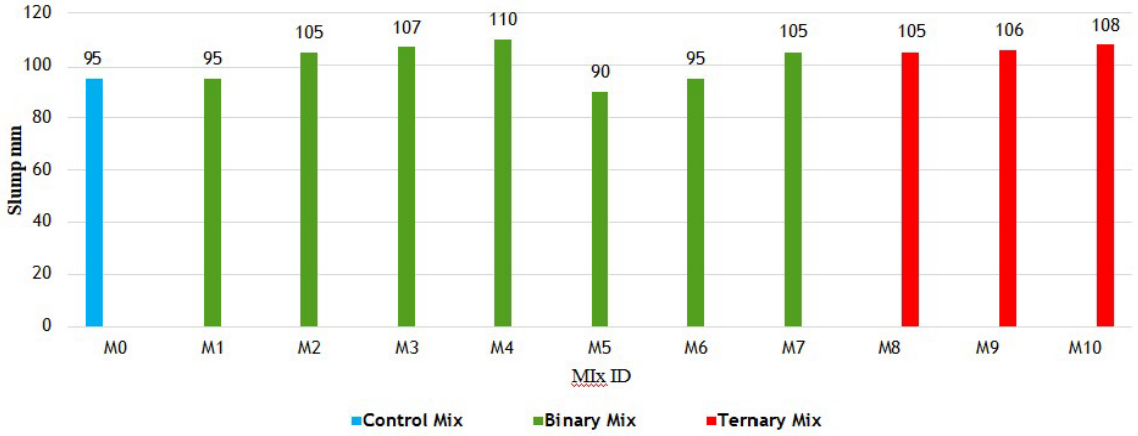


Figure 2. Variation of slump values for control, binary, and ternary concrete mixes incorporating cow dung ash (CDA) and eggshell powder (ESP).

As shown in Figure 2, the slump value increases with increasing CDA content, while ESP initially reduces workability before stabilizing at higher replacement levels.

5.2 Compressive Strength of Concrete

The compressive strength of concrete mixes incorporating cow dung ash (CDA) and eggshell powder (ESP) was evaluated at 7 and 28 days, and the results are presented in Table 4.

Table 4. Compressive Strength of Concrete Mixes

Mix ID	CDA (%)	ESP (%)	7-Day Strength (MPa)	28-Day Strength (MPa)
M_0	0	0	24.3	29.34
M_1	2.5	0	26.3	31.2
M_2	5	0	14.5	20.6
M_3	7.5	0	8.0	15.0
M_4	10	0	6.8	13.6
M_5	0	2.5	22.9	32.2
M_6	0	5	24.0	34.3
M_7	0	7.5	21.3	27.4
M_8	2.5	2.5	23.2	33.0
M_9	2.5	5	25.0	35.3
M_{10}	2.5	7.5	20.2	28.6

The compressive strength results for all concrete mixes at 7 and 28 days are presented in Table 4 and illustrated in Figure 2. The control mix (M_0) exhibited a compressive strength of 24.3 MPa and 29.34 MPa at 7 and 28 days, respectively.

Among the binary mixes, M_1 (2.5% CDA) showed an increase in compressive strength compared to the control mix at both curing ages, while further increase in CDA content M_2–M_4) resulted in a significant reduction in strength. For ESP-based mixes, M_6 (5% ESP) achieved the highest compressive strength among binary combinations, reaching 34.3 MPa at 28 days.

In the ternary mixes, M_9 (2.5% CDA + 5% ESP) exhibited the maximum compressive strength of 35.3 MPa at 28 days, which is higher than both control and binary mixes. However, further increase in ESP content (M_{10}) led to a reduction in strength.

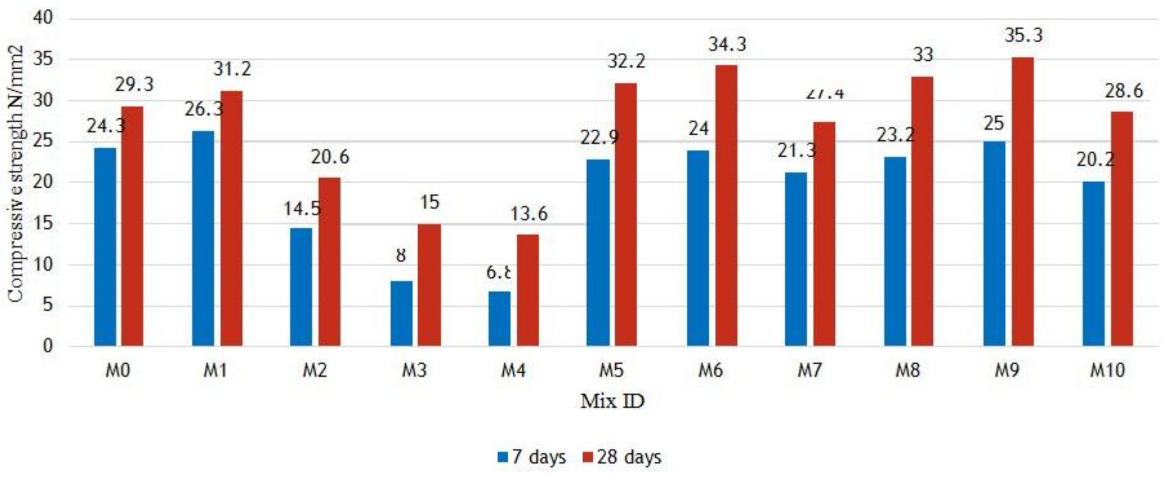
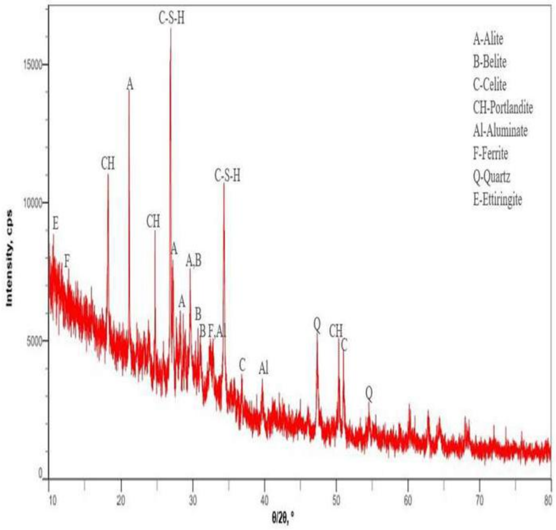


Figure 3 shows the variation in compressive strength of concrete mixes at different curing ages. The ternary mix (M_9) exhibits the highest strength, indicating a synergistic interaction between CDA and ESP.

5.3 Microstructural Analysis (XRD)

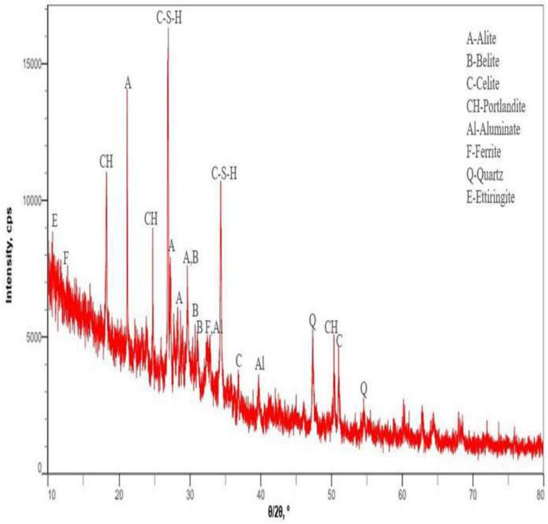
The X-ray diffraction (XRD) patterns obtained for the control concrete mix (M_0) and the optimized ternary mix (M_9) are presented in Figures 3 and 4, respectively.

The diffraction pattern of the control mix (M_0) is shown in Figure 4.



The XRD pattern indicates the presence of "Qमुख hydration products such as portlandite (CH), alite (A), belite (B), quartz (Q), and calcium silicate hydrate (C–S–H) gel. The observed peaks confirm the typical hydration behavior of conventional concrete.

The XRD pattern of the optimized ternary mix (M_9) is presented in Figure 5.

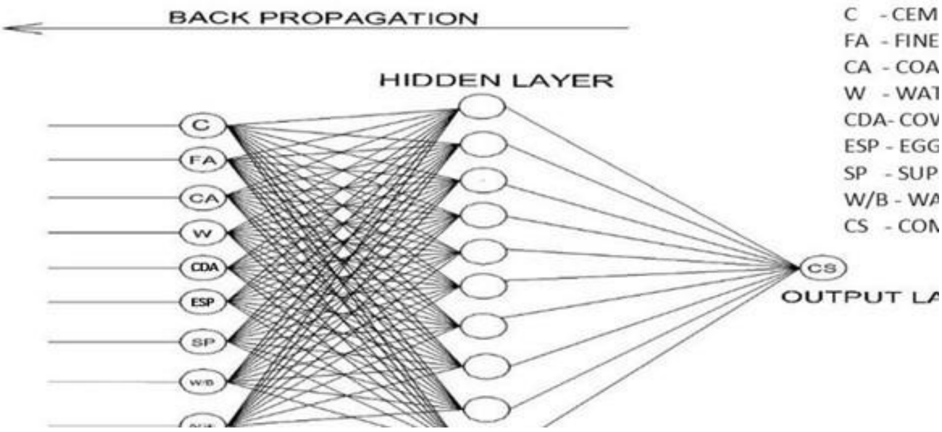


Compared to the control mix, the optimized mix exhibits higher intensity peaks corresponding to C–S–H gel and relatively reduced portlandite (CH) peaks. The presence of quartz and other minor phases is also observed.

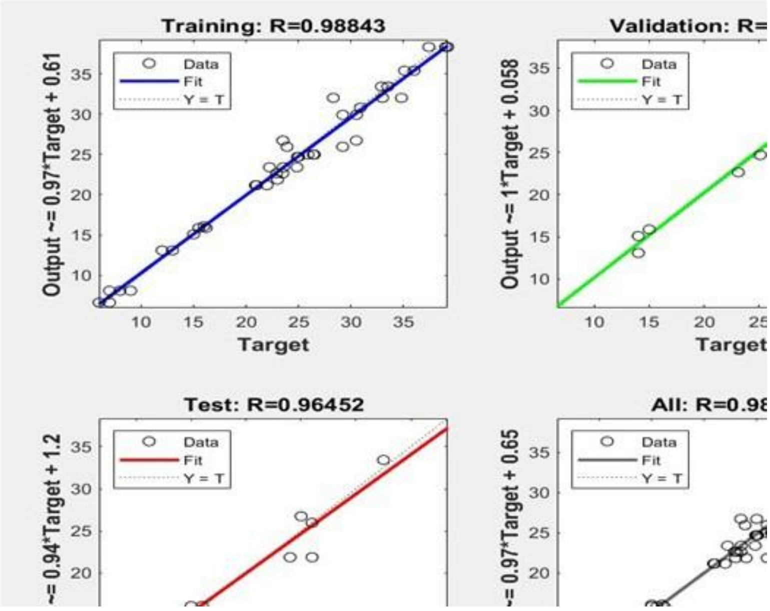
The comparative analysis of Figures 3 and 4 indicates a noticeable change in phase composition between the control and modified concrete mixes.

5.4 ANN-Based Prediction Results

An artificial neural network (ANN) model was developed to predict the compressive strength of concrete mixes based on input parameters such as mix proportions and curing age. The architecture of the developed ANN model is shown in Figure 6.

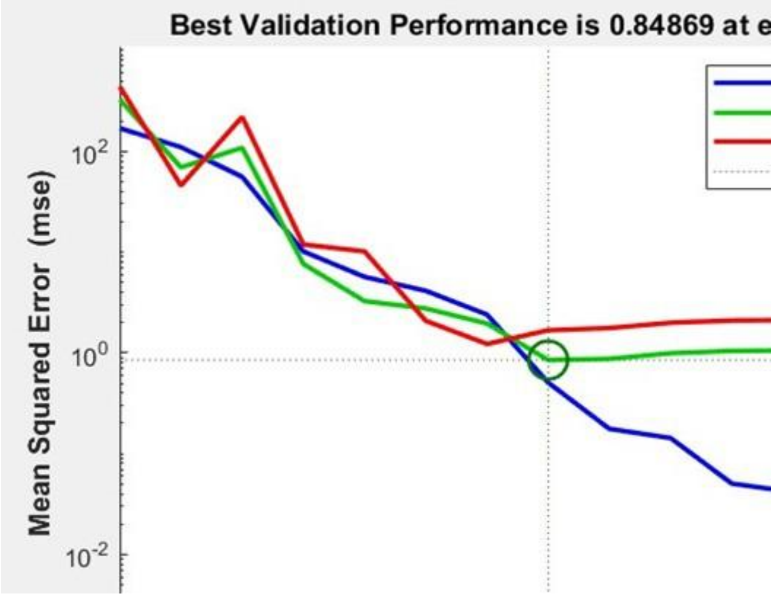


The relationship between the experimental and predicted compressive strength values is illustrated in Figure 7.



The regression plot indicates a strong correlation between predicted and experimental values, with a high coefficient of determination ($R^2 \approx 0.9645$).

The performance of the ANN model in terms of mean squared error during training, validation, and testing phases is presented in Figure 8.



The model achieved optimal validation performance with a minimum mean squared error (MSE) of approximately 0.84869 at an early training stage.

VI. DISCUSSION

The experimental results demonstrate that the performance of concrete incorporating cow dung ash (CDA) and eggshell powder (ESP) is governed by a complex interaction between physical effects, chemical composition, and microstructural evolution. The observed variations in workability and compressive strength are primarily influenced by particle characteristics and their role in hydration mechanisms. Similar observations have been reported in recent studies on waste-based cementitious systems, where both physical and chemical interactions contribute to performance enhancement (Amin et al., 2022; Wang et al., 2023; Alsharari et al., 2022).

6.1 Workability Behavior

The increase in workability with higher CDA content is primarily associated with its lower specific gravity and porous structure, which enhances internal lubrication within the mix and reduces inter-particle friction. Similar observations have been reported in studies involving biomass ashes, where improved flowability is attributed to reduced particle density and increased water retention capacity (Kamat et al., 2021; Worku et al., 2023; Mathur & Chhipa, 2021).

In contrast, the initial reduction in slump observed with ESP incorporation can be attributed to its finer particle size and higher surface area, which increases water demand. This behavior aligns with findings reported in previous studies (Ashraf & Doh, 2020; Chen et al., 2022; Nandhini & Karthikeyan, 2021). However, at moderate replacement levels, the combined use of CDA and ESP results in improved workability and cohesion, indicating enhanced particle packing and dispersion effects in ternary systems.

6.2 Compressive Strength Development

The compressive strength results indicate that the mechanical performance of concrete is highly sensitive to the replacement level of cement. At lower replacement levels, strength enhancement can be attributed to the combined effect of particle packing and secondary hydration reactions. The fine particles of CDA and ESP act as micro-fillers, reducing voids and improving matrix density. In addition, CDA contributes reactive silica (SiO_2), which reacts with calcium hydroxide (CH) generated during cement hydration to form additional calcium silicate hydrate (C–S–H) gel. This pozzolanic reaction is a key mechanism for strength enhancement in blended cement systems (Mehta & Monteiro, 2014; Rath & Madhav Rao, 2023).

The role of ESP is particularly significant due to its high calcium oxide (CaO) content, which promotes hydration and accelerates the formation of cementitious products. Recent studies have shown that calcium-rich additives enhance hydration kinetics and improve both early and later-age strength (Paruthi et al., 2023; Khalid et al., 2023; Maglad et al., 2024).

The superior performance of the ternary mix (M_9) can be attributed to the synergistic interaction between CDA and ESP, where silica from CDA and calcium from ESP jointly contribute to enhanced C–S–H formation. Similar synergistic effects have been reported in multi-component systems involving silica-rich and calcium-rich materials (Deshpande et al., 2018; Rasid et al., 2022; Ates et al., 2023).At highe r replacement levels, a reduction in compressive strength is observed due to the dilution effect, where reduced cement content limits binder formation. Additionally, incomplete reaction of excess supplementary materials may lead to weaker interfacial zones within the concrete matrix (Kamat et al., 2021; Wang et al., 2023; Xuan et al., 2023).

6.3 Microstructural Interpretation (XRD Analysis)

The XRD results provide strong microstructural evidence supporting the observed strength trends. The control mix exhibits prominent peaks corresponding to portlandite (CH), indicating the presence of unreacted calcium hydroxide. In contrast, the optimized mix (M_9) shows increased intensity of C–S–H peaks and reduced CH content, indicating that CH is actively consumed in pozzolanic reactions.

The formation of additional C–S–H gel leads to microstructural densification, which directly contributes to improved compressive strength. This transformation is particularly significant, as excessive CH is often associated with increased porosity and reduced durability. Similar findings have been reported in studies involving supplementary cementitious materials (Rath & Madhav Rao, 2023; Chen et al., 2022; Amin et al., 2022).

6.4 ANN Model Performance and Validation

The ANN modeling results further reinforce the reliability of the experimental findings. The high correlation between predicted and experimental values ($R^2 \approx 0.9645$) indicates that the model effectively captures the relationship between mix composition and compressive strength. The improved prediction accuracy near the optimal mix composition suggests that the system exhibits stable and predictable behavior within this range. The successful application of ANN in this study is consistent with recent research demonstrating its effectiveness in modeling nonlinear relationships in concrete systems (Paruthi et al., 2023; Zhang et al., 2024; Zhu et al., 2024).

6.5 Overall Implications

Overall, the findings of this study highlight that the combined use of CDA and ESP can significantly enhance concrete performance when used within optimal limits. The improvement is primarily driven by synergistic chemical interactions and microstructural refinement.

From a sustainability perspective, the utilization of these waste materials offers a viable solution for reducing cement consumption and associated carbon emissions, aligning with global sustainability goals (International Energy Agency [IEA], 2022). Recent studies have emphasized the importance of such waste-based materials in achieving sustainable construction practices and circular economy objectives (Amin et al., 2022; Wang et al., 2023; Alsharari et al., 2022). However, careful control of replacement levels is essential to avoid strength reduction due to dilution effects.

VII. CONCLUSIONS

This study investigated the feasibility of utilizing cow dung ash (CDA) and eggshell powder (ESP) as partial replacements for cement in concrete, with a focus on workability, compressive strength, microstructural characteristics, and predictive modeling. The results demonstrate that the incorporation of CDA and ESP significantly influences both fresh and hardened properties of concrete. The workability of concrete increased with the addition of CDA, while ESP showed a dosage-dependent effect, initially reducing and subsequently improving slump at moderate replacement levels. The combined use of CDA and ESP in ternary mixes resulted in improved cohesion and uniformity.

In terms of mechanical performance, partial replacement at lower levels enhanced compressive strength, whereas higher replacement levels led to strength reduction due to dilution effects. The optimum performance was achieved for the ternary mix containing 2.5% CDA and 5% ESP (M_9), which exhibited superior compressive strength compared to the control mix. This improvement is attributed to the synergistic interaction between silica-rich CDA and calcium-rich ESP. Microstructural analysis using XRD confirmed the formation of increased calcium silicate hydrate (C–S–H) gel and the reduction of portlandite in the optimized mix, indicating enhanced pozzolanic activity and matrix densification. These findings are consistent with the observed improvement in compressive strength.

The ANN model developed in this study demonstrated high prediction accuracy, with a strong correlation between experimental and predicted values. This validates the capability of ANN as an effective tool for predicting concrete properties and optimizing mix design. Overall, the study establishes that CDA and ESP can be effectively utilized as sustainable supplementary cementitious materials when used in optimal proportions. Their combined use not only improves concrete performance but also contributes to waste utilization and reduction in cement consumption, thereby supporting environmentally sustainable construction practices.

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