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Sustainable Eggshell-based Fired Bricks for Additive Manufacturing Application

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ORIGINAL RESEARCH

Abstract— The intensifying demand for cement-created composites (CCCs) owing to the expansion of infrastructure causes negative environmental and exhaustion of natural materials. Besides, dumping agricultural waste and industrial items on landfills leads to adverse effects. Eggshell dust (ESD) was used to partially substitute cement at various proportion, then analysis such as particle size distribution and Brunauer–Emmett–Teller (BET) surface area, soil enhancer, strength and durability, that is sorptivity and absorption degree of concrete was carried out. The dataset obtained via experimentation technique was used to predict and forecast CCCs-created model using machine learning, extreme gradient boosting regressor and validation of the models. The bottommost reduction in compressive strength (CS) was ascertained when ESD was utilized as a cement substitute of 12.5%, which was up to 9.82% lower than the equivalent mix as a control. What's more, the developed CCCs-created model unveiled a pleasing level of consensus with the experimental verdicts, hence signifying their potential pertinency in evaluating the CS outcome in CCCs that integrates ESD.

Keywords— Cement-created composites, Additive manufacturing, Eggshell, extreme gradient boosting regressor, Sorptivity.

1 Introduction

Additive manufacturing is a parasol expression for the production approaches in which dimensional objects are created through computer-controlled method (Akhtar et al. 2022; Cao et al 2022). Disparate from traditional subtractive manufacturing, which removes material from a solid workpiece to obtain the final product, additive manufacturing (including 3D printing) builds components layer by layer based on a digital model (Bahraq et al., 2022; Al-Baghdadi, 2021).This technique permits formation of composite geometries, lessens waste, and propositions of the flexibility in the usage of numerous materials. Material extrusion (MEtx) is a type of AM, besides among most broadly used AM techniques that utilized a continuous composite or thermoplastic material (Devi 2018; Amiri et al. 2021; Baloch et al. 2021). MEtx can be effectively made using cement-created composites through significant amounts of eggshells which is obtained from industrial and public usage of eggs so as to combat waste disposal matters. Waste discarding is very common emergent issue for a cleaner environment (Hill et al. 2008; Sahoo et al. 2020).

Likewise, the creation of construction materials has a noteworthy impact on the environment due to rapid growth and excessive demand on infrastructure such as quality road and modernized buildings that have placed high demand on cement (Nnaemeka and Singh 2020; Faridi 2018; Jhathal 2019).

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Cement is a major construction material widely utilized around the globe

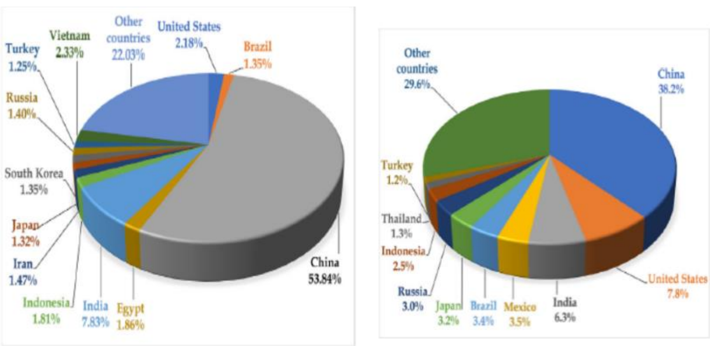

Fig. 1. Global production of (a) cement and (b) egg, during the last 25 years

Fig. 1(a) exemplifies global cement production for the past 25 years, while Fig. 1(b) reveals global egg production in the year. Similarly, the practical utilization of eggshell waste offers an environmentally sustainable solution by reducing landfill disposal and partially substituting cement in construction materials.

Though, recently, greater efforts have been made to transmute eggshells into treasured products, because eggshells have many useful properties or applications, which motivates recent research efforts.

Eggshell has 94.4% calcium carbonate, 1.2% magnesium carbonate, 1.3% calcium phosphate, together with 3.1% organic matter, lot of protein fibers and also connected with crystals (Liu et al. 2021; Hang et al. 2020; Ferraz et al. 2018). An eggshell consists of an outer calcified shell, inner and outer proteinaceous membranes, and a porous structure characterized by chimney-shaped pores irregularly distributed across the shell surface (Tan et al., 2018; Brahomi et al., 2020.

The outermost casing is created attractively much entirely of calcium carbonate (CaCO3) minerals, irregular shape and even size as ascertain via SEM micrograph.

Some of the potential usage ranging from construction materials to value-added products that can be characterized into raw materials for novel product manufacturing as well as effective supplies for catalytic

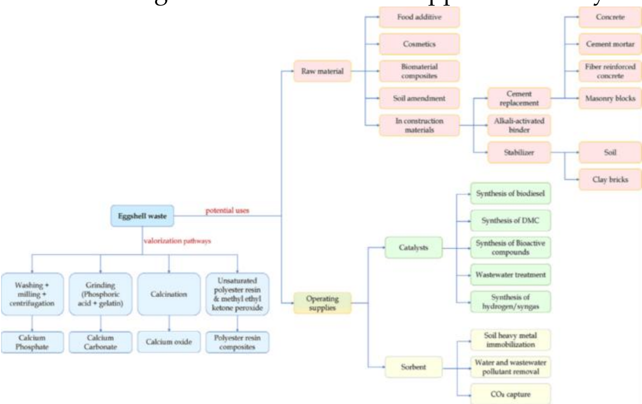

Fig. 2. Potential usages of eggshell with its valorization (FAO and Chriel *et al, 2022*).

çand sorptive applications (Hembrick- Holloman at al. 2020; Ayodele et al. 2019; Oluwaluyi et al. 2018; Nazar et al. 2023). Though eggshells are utilized as a value-added product, vast quantities are still unutilized and discarded into landfills or throw around, especially in developing nations. Fig. 2 abridges the potential usages of eggshell and its valorization pathways.

2 METHODOLOGY

2.1 MATERIALS

2.1.1 CLAY SOIL, ORDINARY PORTLAND CEMENT (OPC) CEM I 53

The OPC had a Blaine specific surface area of 444.8 m^2/kg and a density of 3140 kg/m^3.

2.1.2 FINE AGGREGATES

The fine aggregate consisted of naturally washed siliceous–calcareous sand with a particle size range of 0–4 mm and a density of 2632 kg/m^3. All construction materials were sourced from local suppliers in Nigeria.

2.1.3 EGG SHELL WASTE

Eggshell waste was collected from designated dumping sites within Nigeria. The collected eggshells were thoroughly washed to remove adhering impurities, oven-dried, calcined, ground, and sieved through a 63 µm mesh to produce eggshell dust (ESD), as illustrated in Fig. 3.

2.2 CHARACTERIZATION OF EGGSHELL DUST

Chemical characterization of the processed eggshell dust was conducted in accordance with DIN EN ISO 3262-5 using plasma optical emission spectroscopy. The analysis confirmed an average calcium carbonate ($CaCO_3$) content of 96.8%, classifying the eggshell dust within purity grades B–C. This high $CaCO_3$ content indicates the suitability of ESD as a supplementary cementitious material.

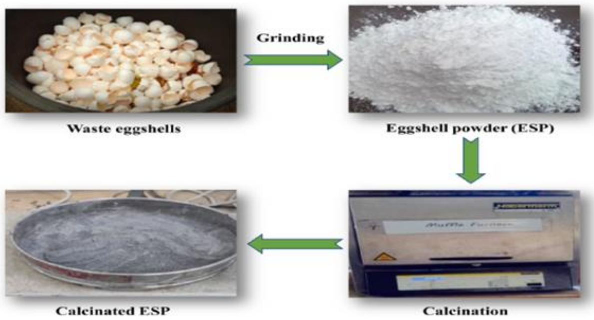

Fig. 3. Eggshell treated from waste to calcinated eggshell dust.

2.3 Mix Proportions and Specimen Preparation

Fired brick specimens were produced to evaluate the suitability of ESD as a partial replacement for cement. A control mix without eggshell dust (E-0%) was prepared, alongside modified mixes containing 2%, 4%, 6%, 8%, and 10% ESD by weight of cement.

All mixes were prepared using a constant water-to-binder ratio of 0.5, where the binder consisted of OPC and eggshell dust. Mechanical mixing was employed to ensure uniform dispersion of materials. The fresh mixtures were cast into molds and subjected to vibration to eliminate entrapped air and improve compaction. After demolding, specimens were cured under controlled conditions prior to testing.

2.4 Mechanical Testing

Uniaxial compressive strength tests were conducted to assess the strength development of the fired bricks incorporating eggshell dust. Tests were performed at curing ages of 7, 14, 21, 28, and 56 days in accordance with ASTM C109/C109M-20.

2.5 Machine Learning Modeling for MEtx-Based CCCs

To support material optimization for material extrusion (MEtx), a subsidiary of additive manufacturing (AM), machine learning modeling was performed using experimental data obtained from compressive strength tests. The use of static or minimally varying input variables was avoided to prevent suboptimal model performance. Input parameters for the predictive models included cement content, water content, sand content, eggshell dust content, and waste lactose. The output variable was the compressive strength proportion of cement-created composites (CCCs) relative to the control mixture.

2.6 Model Development and Validation

Ensemble learning models, specifically Gradient Boosting Regressor (GBR) and Extreme Gradient Boosting Regressor (EGBR), were developed using Python via the Spyder (version 5.1.5) environment under the Anaconda Navigator package (Fig. 4). The experimental dataset was randomly partitioned into training (70%) and testing

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(30%) subsets.
Model performance was evaluated using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE). An R^2 value closer to unity indicates a strong agreement between predicted and experimental results, while lower values indicate increased divergence. Additionally, k-fold cross-validation was employed to assess model robustness and generalization capability.

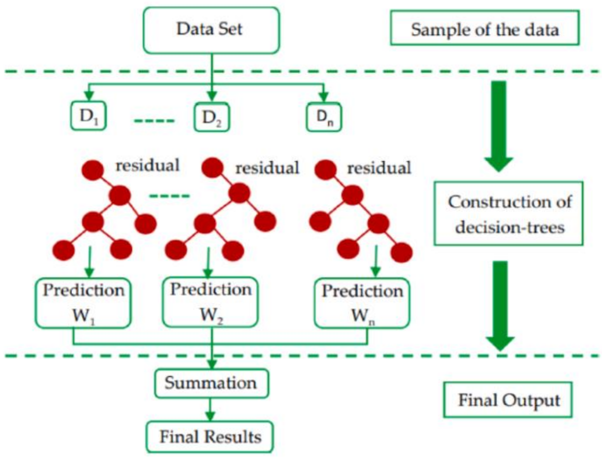

Fig. 3. Outline of Extreme gradient boosting regressor technique

3 RESULTS AND DISCUSSION

3.1 Particle size distribution and Brunauer–Emmett–Teller surface area

The particle size dispersal and processing accurate density as well as BET surface area of cement and ESD are displayed in Fig. 4 (a & b). Eggshell dust possesses an enormous $CaCO_3$ quantityand their physiognomies are equivalent to the calcareous. The outcome from specific gravity and Blaine surface area shows calcium as the major component in an eggshell, and tiny quantities of magnesium and other microelements. It can be ascertained from these outcomes that eggshell dust demonstrates an extreme calcium quantity. It also signifies that the processing approach impels the calcium physiognomies of the ESD. Because after the eggshell undertook crushing as well as oven - drying, the result shows about 50.4% calcium content without calcination. While with calcination, the outcome ranges from 65.4 - 75.3%, and by calcination, CaO can be created from $CaCO_3$. Compare this result with other researchers such as Ayyappa et al. (2020), Akeed et al. (2022) and Nazar et al. (2023) that returned the same verdicts. Hence, the usage of these as add-on cementitious materials in the creation of cement-created composites might lead to noteworthy energy and cost savings, as well as environmental contamination minimizer (Akeed et al. 2022; Khan et al. 2022).

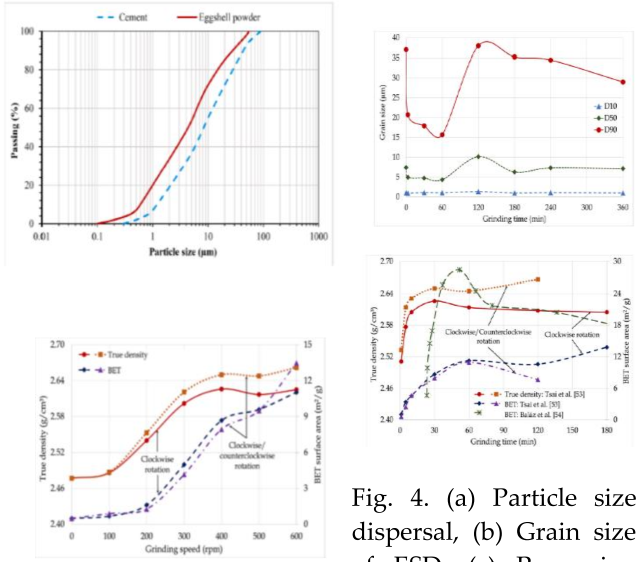

Fig. 4. (a) Particle size dispersal, (b) Grain size of ESD, (c) Processing accurate density and BET surface area ESD with grinding time impact and (d) The density and BET surface area of the eggshell dust (ESD) and the results compared with findings by other investigators.

3.2 ESD as a soil Enhancer

Figs. 5 – 7 displays the outcome of scrutiny using ESD to enhance soil physiognomies. Soil enrichment refers to the modification of any physiognomies of a soil to enhance its engineering (plasticity index, compression, angle of friction and permeability) functions. Soil enrichment via calcium-created enhancers like cement or other binder encompasses various dissimilar methods; viz, clustering, hydration of cementitious, substitution of cation, pozzolanic reaction and flocculation. All the processes can be achieved by here incorporation of ESD, while cement can only contribute slightly. Fig. 5a demonstrates that with enrichment with various proportions of ESD during compaction investigation, maximum dry density (MDD) lessens at higher The proportion of eggshell powder (ESP) used as a soil enhancer in the clay soil mixture. Similarly, the reduction in the MDD might be due to the moderately lesser specific gravity of ESD that is blended with the clay contents. While Fig. 5b outcome of unsoaked California bearing ratio (CBR) values for clay contents with ESD enhancer style was that the increase in ESD enhancer displays an enhancement in the CBR value. Greater values of CBR are more desirable for various construction works, because CBR values designate whether clay contents strength can bear a vertical load or not. This improvement in the CBR might be owing to the chemical reaction among the clay contents and the creation of calcium silicate hydrate (C-S-H) gel, which is ascribed as strength gain. Likewise, Fig. 6 which shows Atterberg limit properties like liquid limit (LL) as well as plastic limit (PL), at various ESD addictive shows that both LL and PL decline with the addition of ESD to the soil. Addiction of ESD to clay soils activates a colloidal action that entails replacing calcium for cations on the soil exterior. This causes higher flocculation and aggregation

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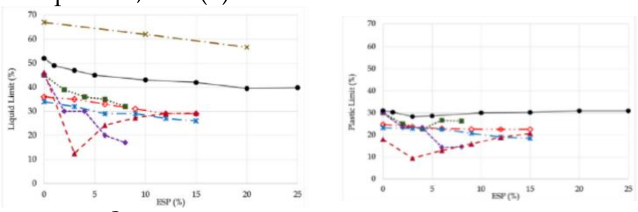
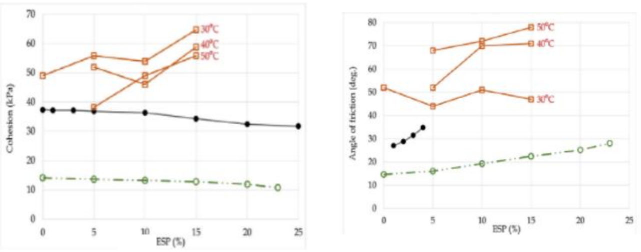
within the soil particles which in turn make the clay soils have lesser plastic contents. Figure 7 (a–c) illustrates the shear behavior of clay, showing that increasing the proportion of ESD as a soil enhancer generally increases the clay's internal friction angle, while causing a slight decrease in cohesion, which is a steeper approach for clay and other problematic soils. It was ascertained that clay contents agglomeration occurs owing to the introduction of ESD. Owing to clustering, the size of the clay contents increases in and this triggers an increase in the angle of friction of the clay contents and vice versa (Devi 2018; Baloch et al. 2021). The enhancement in the angle of internal friction values without much impact on its cohesion specifies a good increase in the shear strength of the clay contents. Similarly, Fig. 7(d) displays the results of various proportions of blended ESD-clay contents on unconfined compressive strength (UCS). This ascertain that UCS of the clay contents improved up to 12% quantities of ESD enhancer and then reduction in strength hereafter. Nevertheless, the UCS of the clay contents with greater ESD enhancer is still beyond that of unenriched clay soils (Liu et al. 2021; Ferraz et al. 2018).

Fig. 5. Outcome of blended ESD-clay contents on a) Compaction, and (b) CBR.



a b

Fig. 6. Outcome of blended ESD-clay contents on a) Liquid limit, and (b) Plastic limit.



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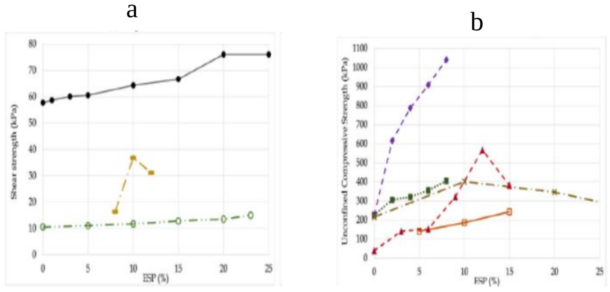

c d

Fig. 7. Outcome of blended ESD-clay contents on a) Angle of friction, and (b) Cohesion, (c) shear strength, and d) Unconfined Strength test.

3.3 Impact of ESD as an Enhancer of Fired Bricks on Strength Scrutiny

Fig. 8 – 10 demonstrate the impact of ESD enhancer on various fired bricks. After the addition of ESD to the clay contents, an increase in compressive strength of clay contents was noticed. ESD possesses lesser density than clay, and the introduction of ESD did not lessen the density of the ESD-created fired bricks. This is owing to the fact that the fine ESD contents utilized in the reinforcement phase sealed up the pores available within the clay structure, which in turn leads to lesser number of pores in the ESD-based fired clay bricks. This can be due to pozzolanic reaction, cation swapping, flocculation and clustering processes. Conversely, pozzolanic reaction is a time - reliant technique that usually transpires when Al_2O_3, SiO_2 together with $Ca(OH)_2$ reacted to create cementitious composites like C-A-H (calcium aluminate hydrate) as well as C-S-H (calcium silicate hydrate) that contribute momentously to the strength improvement of ESD-created fired bricks. Nevertheless, the enhancement with ESD greater than the optimum level results in a lesser strength value. Hence, the water absorption rate momentously reduces with the improvement of ESD. Even though there is momentous enhancement in the compressive strength of ESD-created fired clay brick; to obtain an optimal strength rest, its burning temperature must be roughly 5 hours. This perhaps can owe to the pozzolanic reaction not stirring the extra ESD values (Nnaemeka and Singh 2020; Jhathal 2019). Though bricks date back to the olden days as widely utilized building materials, but its key weaknesses as construction materials are their greater water absorption, little strength and dimensional stability specifically when they are utilized for flood construction or storey- structure works.

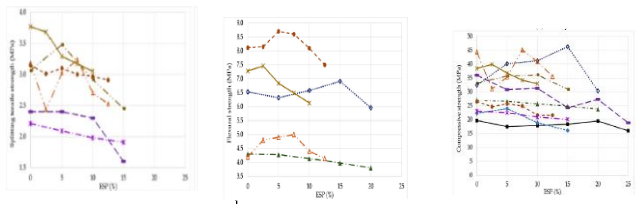

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Fig. 8. Outcome of blended ESD-fired bricks on a) Split tensile strength, b) Flexural test and c) Compressive strength at 28 days

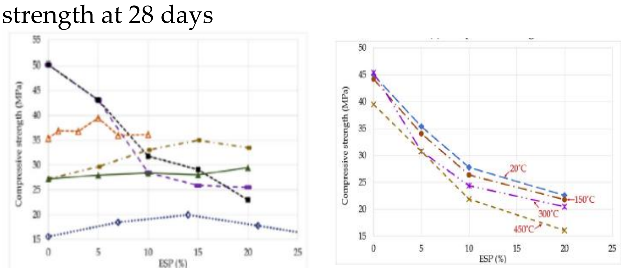

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Fig. 9. Outcome of hot temperature on blended ESD-fired bricks on a) compressive strength at lower temperature, b) compressive strength at greater

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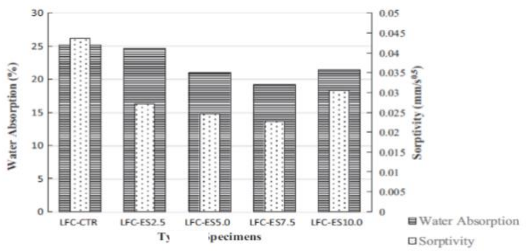
3.4 Absorption and sorptivity rates of ESD-created fired bricks

Fig. 10 (a & b) displays the impacts of water absorption and sorptivity on ESD-created fired bricks at 60 days.As the results show that water absorption lessens between 5% to 10% partial substitution of ESD, then increased after 10% proportion. The absorptions of all samples were directly proportional to the square root of time which gave R^2 value closely to accurate(Fig. 10a). While sorptivity outcome below 10% especially at 7.5% signifies significantly decreased when linked to the control mix. Nevertheless, integration of 10% ESD in fired bricks shows contrary outcome, i.e. greater values of sorptivity values This can also be due to ability of ESD in providing superfluous quantities of calcium materials which are creator of secondary C–S–H gel and also act as helpful filler for the blended clay contents. Consequently, the gel seals up the prevailing voids in the concrete and then results in a lesser rate of water absorption (Ayodele et al. 2019; Oluwaluyi et al. 2018). The integration of ESD in fired bricks lessened the water absorption, when compared with the control mix. Similar research also ascertains that the amalgamation of ESD in normal weight concrete leads to lesser water absorption



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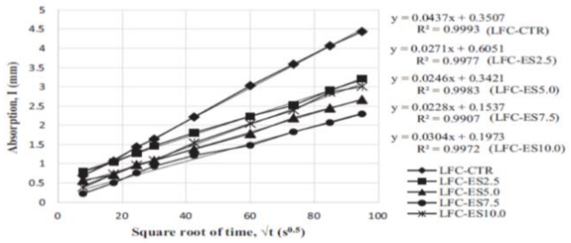
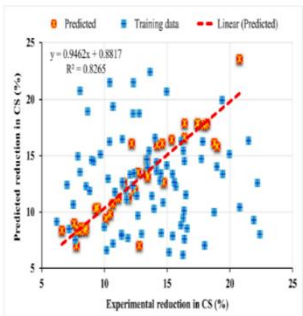


b

Fig. 10. Effects of blended ESD-fired bricks on absoption and a) Sorptivity, (b) Square root of time at 60 days

3.6 Outcome of Modelling though MEtx methods via Gradient Boosting Regression model on Strength derived from ESD Research

Figs. 11 &12 signifies the outcome of modeling though MEtx techniques via gradient Boosting regression (GBR) and Extreme gradient boosting regressor (EGBR) model. It ascertains that CS can be augmented with 7–12% ESD blended ratio. Other investigators advocate that these models performed aptly in evaluating the CS of ESD-improved cementitious composites atshigher degree of precision. From the figure, it was ascertained that there was just a minor variation between the experimental and projected CS, signifying that the models adequately predicted strength. With an $R^2$of 0.84, the state of agreement between the detected and forecast outcomes was seen to be beneficial. Spreading of observed, forecast, and error of GBR model values was 5.73% which was the largest, with mean of 1.18%. Additionally, it was discovered that the error values for 20 samplings were lower than 0.54%; for 6 samplings, the error value stand at 0.49% and 1.2%; for 9 samplings, all created on the proportional dispersal of the errors. The verdicts of the EGBR approach predicting the CS of ESD-based fired bricks reveal greater R^2 value of 0.94, which isa robust precision. The utmost error was noticed to be 2.13%, and the mean error was estimated at 0.79% as shown on (Fig. 12). Similarly, for 21 data points, the error values were under 0.49%; for 10 data- points, the errors were between 0.52% and 0.9%; while for 4 data-points, the errors were between 1.1% and 1.9%; based on the spreading error. EGBR model was highly accurate owing to its tree-created ensemble learning approach that regulates output by creating submodels than the GBR model, though both are very good and this is in agreement with the studies done by previous scholars (Tan et al. 2018; Nnaemeka and Singh 2020; Brahomi et al. 2020 and Jhathal 2019).



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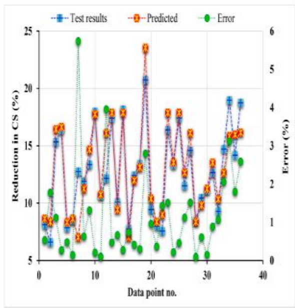

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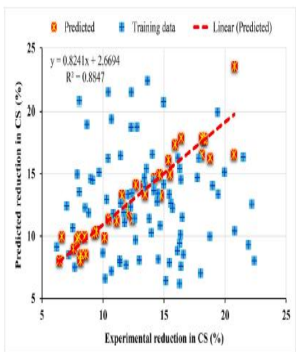
Fig. 11. Outcome of GBR model, a) Connection between practical and projected, b) Spreading error and actual predictable contents.



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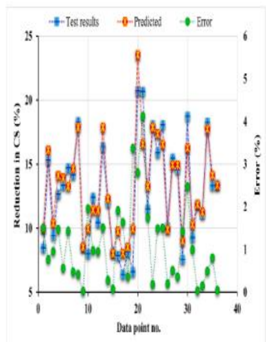

b

Fig. 12. Outcome of EGBR model, a) Spreading error and actual predictable contents and b) Connection between practical and projected.

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4 CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The following conclusions were made from experimental research work.

1. Eggshell dust exhibited a specific gravity ranging from 2.08 to 2.52, which is lower than that of Ordinary Portland Cement, indicating its suitability as a lightweight supplementary material in cement-created composites (CCCs).
2. The specific surface area of ESD varied between 301 and 1404 m²/kg, with calcination temperature playing a significant role in enhancing surface characteristics and reactivity.
3. The minimum reduction in compressive strength was observed at a cement replacement level of 12.5% ESD, corresponding to a reduction of only 9.82% compared with the control mix.
4. Acceptable mechanical performance of CCCs was achieved when ESD was used as a partial cement substitute within the range of 12.5% to 15%.
5. Machine learning models developed for compressive strength prediction showed strong agreement with experimental results, confirming their reliability for performance evaluation of ESD-incorporated CCCs.
6. The Gradient Boosting Regressor (GBR) and Extreme Gradient Boosting Regressor (EGBR) models achieved coefficient of determination (R^2) values of 0.84 and 0.94, respectively.
7. The EGBR model demonstrated superior predictive accuracy due to its tree-based ensemble learning structure, although both models were effective for compressive strength forecasting.

4.2 RECOMMENDATIONS

1. Eggshell dust may be safely used as a partial cement replacement in cement-created composites at levels between 12.5% and 15% without significant compromise in mechanical performance.
2. Higher ESD contents of up to 25% are recommended for soil and clay enhancement applications, where strength requirements are less stringent.
3. For fired brick production, ESD replacement levels within the range of 20% to 40% are recommended, particularly where sustainability and waste valorization are prioritized.
4. The Extreme Gradient Boosting Regressor (EGBR) model is recommended for predictive analysis and optimization of MEtx-based cement-created composites due to its superior accuracy.
5. Future studies should explore long-term durability, thermal performance, and large-scale additive manufacturing trials of ESD-based cement composites.

REFERENCES

Akbar, F. H. A. (2018). Application of eggshell wastes as valuable and utilizable products: A review. *Research in Agricultural Engineering, 64*(2), 104–114.

Akhtar, M. N., Jameel, M., Ibrahim, Z., & Bunnori, N. M. (2022). Incorporation of recycled aggregates and silica fume in concrete: An environmental savior—a systematic review. *Journal of Materials Research and Technology, 20*, 4525–4544. https://doi.org/10.1016/j.jmrt.2022.09.021

Akeed, M. H., Qaidi, S., Ahmed, H. U., Faraj, R. H., Mohammed, A. S., Emad, W., Tayeh, B. A., & Azevedo, A. R. G. (2022). Ultra-high-performance fiber-reinforced concrete. Part IV: Durability properties, cost assessment, applications, and challenges. *Case Studies in Construction Materials, 17*, e01271. https://doi.org/10.1016/j.cscm.2022.e01271

Al-Baghdadi, H. M. (2021). Experimental study on sulfate resistance of concrete with recycled aggregate modified with polyvinyl alcohol (PVA). *Case Studies in Construction Materials, 14*, e00527. https://doi.org/10.1016/j.cscm.2021.e00527

Amiri, M., Hatami, F., & Golafshani, E. M. (2021). Evaluating the synergic effect of waste rubber powder and recycled concrete aggregate on mechanical properties and durability of concrete. *Case Studies in Construction Materials, 15*, e00639. https://doi.org/10.1016/j.cscm.2021.e00639

ASTM International. (2016). *ASTM C90-16a: Standard specification for loadbearing concrete masonry units*. ASTM International.

Ayodele, A. L., Oketope, O. M., & Olatunde, O. S. (2019). Effect of sawdust ash and eggshell ash on selected engineering properties of laterized bricks for low-cost housing. *Nigerian Journal of Technology, 38*, 278–282. https://doi.org/10.4314/njt.v38i2.1

Ayyappa, R. A., Sandeep, R. B., Yadav, G. S., & Dara, S. S. (2020). Partial replacement of cement and coarse aggregate by eggshell powder and coconut shells. *International Journal of Innovative Technology and Exploring Engineering, 9*, 1242–1246. https://doi.org/10.35940/ijitee.D1573.029420

Bahraq, A. A., Jose, J., Shameem, M., & Maslehuddin, M. (2022). A review on treatment techniques to improve the durability of recycled aggregate concrete: Enhancement mechanisms, performance and cost analysis. *Journal of Building Engineering, 55*, 104713. https://doi.org/10.1016/j.jobe.2022.104713

Baloch, W. L., Siad, H., Lachemi, M., & Sahmaran, M. (2021). A review on the durability of concrete-to-concrete bond in recent rehabilitated structures. *Journal of Building Engineering, 44*, 103315. https://doi.org/10.1016/j.jobe.2021.103315

Barkhad, M. S., Abu-Jdayil, B., Iqbal, M. Z., & Mourad, A. H. I. (2020). Thermal insulation using biodegradable poly(lactic acid)/date pit composites. *Construction and Building Materials, 261*, 120533. https://doi.org/10.1016/j.conbuildmat.2020.120533

Bhaskaran, H., John, L., Neethu, P. M., & Sebastian, T. (2016). Study on egg shell concrete. *International Journal of Engineering Research and Technology, 4*, 4–6.

Cao, Y., Bao, J., Zhang, P., Sun, Y., & Cui, Y. (2022). A state-of-the-art review on the durability of seawater coral aggregate concrete exposed to marine environment. *Journal of Building Engineering, 60*, 105199. https://doi.org/10.1016/j.jobe.2022.105199

Ferraz, E., Gamelas, J. A. F., Coroado, J., Monteiro, C., & Rocha, F. (2018). Eggshell waste to produce building lime: Calcium oxide reactivity, industrial, environmental and economic implications. *Materials and Structures, 51*, 115. https://doi.org/10.1617/s11527-018-1243-7

Hang, X., **et al.** (2020). Environmental impact and quality assessment of using eggshell powder incorporated in lightweight foamed concrete. *Construction and Building Materials, 244*, 118341. https://doi.org/10.1016/j.conbuildmat.2020.118341

Hembrick-Holloman, V., Samuel, T., Mohammed, Z., Jeelani, S., & Rangari, V. K. (2020). Ecofriendly production of bioactive tissue engineering scaffolds derived from egg- and sea-shells. *Journal of Materials Research, 9*(6), 13729–13739.

Jhatial, S. (2019). Eggshell powder as partial cement replacement and its effect on the workability and compressive strength of concrete. *International Journal of Advanced Applied Science, 6*(9), 71–75.

Khan, M., Cao, M., Chu, S. H., & Ali, M. (2022). Properties of hybrid steel–basalt fiber reinforced concrete exposed to different surrounding conditions. *Construction and Building Materials, 322*, 126340. https://doi.org/10.1016/j.conbuildmat.2022.126340

Liu, Z., Lei, Q., & Xing, S. (2019). Mechanical characteristics of wood, ceramic, metal and carbon fiber-based PLA composites fabricated by FDM. *Journal of Materials Research, 8*(5), 3741–3751.

Nazar, S., Yang, J., Ashraf, M., Aslam, F., Javed, M. F., Eldin, S. M., & Xie, J. (2023). Formulation and characterization of cleaner one-part novel fly ash/lime-based alkali-activated material. *Journal of Materials Research and Technology, 23*, 3821–3839. https://doi.org/10.1016/j.jmrt.2023.02.022

Nnaemeka, O. F., & Singh, N. B. (2020). Durability properties of geopolymer concrete made from fly ash in presence of kaolin. *Materials Today: Proceedings, 29*, 781–784. https://doi.org/10.1016/j.matpr.2020.04.696

Oluwatuyi, O. E., Adeola, B. O., Alhassan, E. A., Nnochiri, E. S., Modupe, A. E., Elemile, O. O., Obayanju, T., & Akerele, G. (2018). Ameliorating effect of milled eggshell on cement stabilized lateritic soil for highway construction. *Case Studies in Construction Materials, 9*, e00191. https://doi.org/10.1016/j.cscm.2018.e00191

Pokorski, P., & Hoffmann, M. (2022). Valorization of bio-waste eggshell as a viable source of dietary calcium for confectionery products. *Journal of the Science of Food and Agriculture, 102*(8), 3193–3203.

Sahoo, S., Mahapatra, T. R., Priyadarshini, N., Mahapatra, S., Naik, S., & Jaypuria, S. (2020). Influence of water–binder ratio on strength and acid resistance of concrete made up of mineral admixture as supplementary cementitious material. *Materials Today: Proceedings, 26*, 796–803. https://doi.org/10.1016/j.matpr.2020.01.028

Subathra Devi, V. (2018). Durability properties of multiple blended concrete. *Construction and Building Materials, 179*, 649–660. https://doi.org/10.1016/j.conbuildmat.2018.05.056

Tan, Y. Y., Doh, S. I., & Chin, S. C. (2018). Eggshell as a partial cement replacement in concrete development. *Magazine of Concrete Research, 70*, 662–670. https://doi.org/10.1680/jmacr.17.00003