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STOCHASTIC OPTIMIZATION OF EXPANDED POLYSTYRENE SIZE AND PROPORTION IN CONCRETE USING MACHINE LEARNING

Abstract. This paper presents a study on the prediction of the impact of incorporating EPS into concrete using ML algorithms. A dataset of 125 samples from reputable international journals was analyzed using Python tools. The primary objective of this study is to develop a reliable algorithm to optimize the size and proportions of EPS beads in concrete mixes without compromising 28-day compressive strength. Gradient Boosting Regression, Random Forest Regression, and XGBoost models were applied and evaluated using MAE, MSE, RMSE, and R^2 score to select the best predictive model. Based on this newly developed algorithm, an experimental test was conducted, and the results closely matched the predicted values with only slight differences. The study recommends further experimental investigations to understand the interaction between EPS beads and other concrete ingredients. It also emphasizes the importance of multidisciplinary approaches and mitigation strategies for better integration of EPS in concrete design.

Keywords: concrete, compressive strength, machine learning, Expanded Polystyrene, Python.

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Introduction. The adoption of innovative concrete systems, such as Expanded Polystyrene (EPS), has significantly influenced the field of structural engineering. As concrete is heavy in nature and its production isn't environmentally friendly, the attention of the concrete technology is becoming toward the material consumption reduction, improve structural efficiency, and achieve sustainability goals. Expanded polystyrene is one of the promising materials that has gained an increasing attention from the construction industry as a lightweight aggregate in concrete due to its potential to improve thermal insulation, reduced dead weight, and offer a sustainable alternative to conventional aggregates. Studies show that the introduction of EPS in concrete mixtures leads to significant reductions in the overall weight of the concrete [1-3].

Nevertheless, incorporating EPS into concrete poses challenges to the mechanical properties, primarily influenced by the size and proportion of EPS beads. To alleviate these challenges, different studies examined the effects of varying EPS proportions and sizes on the mechanical properties of concrete, focusing on optimizing for different structural applications. It was found in [4,5] that by examining the impact of cement and EPS bead ratios on compressive strength and density of lightweight concrete that increasing the cement to EPS ratio enhanced both density and compressive strength. To evaluate the influence of incorporating EPS beads into concrete on two primary concrete properties: density and compressive strength, an experimental study conducted by introducing different proportions of EPS beads into the concrete mix as a partial replacement for conventional aggregate [6]. The results showcased incorporating EPS beads reduces concrete density, making it lighter and with increasing EPS content the compressive strength which limits the structural applications of such mixes. It was indicated in [7], exploring the physical and mechanical properties of voided concrete containing EPS beads, that compressive strength and EPS volumes are negatively correlated. The study highlights a key finding that supports the discussion in [6] a negative correlation exists between compressive strength and the volume of EPS beads in concrete. The reduced load transfer efficiency between the matrix and EPS particles is a key factor, as stated by [8-10]. Despite this drawback, the ductility of the concrete can be improved due to the energy-absorbing characteristics of EPS. Hybrid mixtures combining EPS with other lightweight aggregates or fibers have been explored to balance strength and ductility [11-14]. Research in [15,16] investigates the mechanical properties of hybrid fiber-reinforced expanded polystyrene lightweight aggregate concrete. It focuses on understanding how different types of fibers, when combined with EPS aggregates, influence the concrete's strength, ductility, and overall performance. The inclusion of EPS is consistently associated with a reduction in compressive strength. Researchers have demonstrated that as the percentage of EPS replacement increases, the compressive strength decreases. This is attributed to the lower stiffness and weaker bonding capacity of EPS particles compared to traditional aggregates [12,17-19]. However, studies indicate that optimizing the mix design, such as using EPS beads with surface treatments or incorporating supplementary cementitious materials, can mitigate strength losses [20,21]. A study [22] focuses on the uniaxial compressive stress-strain behavior of expanded polystyrene concrete, which is widely used as a lightweight concrete in construction. The research presents experimental data on the stress-strain relationship of EPS concrete, analyzing how the inclusion of EPS beads influences its compressive strength and deformation characteristics. The findings reveal that EPS concrete exhibits a distinctive stress-strain curve compared to conventional concrete.

Despite the significant advancements in experimental and numerical methodologies, several gaps persist in the existing body of knowledge. The correlation between EPS beads and surrounding ingredients in concrete remains underexplored. Studies addressing the long-term performance and fatigue behavior of EPS concrete under various loading conditions are limited [23]. There is a lack of standardized guidelines for the design, testing, and implementation of EPS concrete structures even in ACI 544.1R-96 and ASCE/SEI 41. These all gaps necessitate multidisciplinary approaches, integrating advanced materials science, computational modelling, and environmental engineering to fully realize the benefits of the EPS concrete technology.

This study integrates advancements in machine learning (ML) models such as Gradient Boosting Regression, Random Forest and XGBoost algorithms with the theoretical concepts and practical applications to address complex challenges and develop innovative solutions for sustainable and efficient construction practices. Based on the outcomes of these algorithms, experimental tests are conducted on relevant samples. The primary aim of this study is to stochastically develop the scatter plots that depicts the interaction of EPS beads with the nature of the surrounding materials and their collective impact on the compressive strength of concrete. Optimizing EPS size and proportions without compromising the compressive strength of the concrete is a key emphasize in this study. The validation of this approach is proved by experimental tests. At the end, this study concludes with a proposal of a simple mix design approach for EPS concrete that involves the determination of three key parameters to avoid extensive trial mixes:

a. The correlation of the EPS beads with the overall compressive strength of EPS concrete;

b. Fixing the target compressive strength to be achieved;

c. Estimating the potential compressive strength of the EPS concrete based on the selected materials and mix proportions based on the developed algorithm.

Materials and methods. Emphasizing on the wide range of the size and proportion of EPS beads, a dataset of 125 samples from different experimental research that were published in different international journals was collected to ensure the wider dataset range of the EPS Concrete Mixture matrixes. This dataset considers variety of proportions of cement, silica fume, aggregates, EPS beads, water, and admixtures. This collection of datasets was undertaken by carefully selecting all input variables so that it represents the wide range of EPS concrete compressive strength. Finally, experimental tests were conducted on relevant samples using a MATEST Compressive Strenghth Testing Machine (Fig. 1), in accordance with the developed algorithms.

The procedure adopted in this study involves the following steps:

1. Dataset Collection: A diverse collection of datasets pertaining to EPS concrete mixture matrices was carefully gathered from experimental tests conducted by various researchers by considering the compressive strength, the average size of EPS beads and the proportion of EPS incorporated into the mixtures. The dataset contains 125 samples in which 9 independent variables and 1 output variable. One cubic meter of concrete is considered for the input dataset and the variables: cement, silica fume, water, superplasticizer, coarse aggregates, EPS beads, and fine aggregates. In this study, 28-day compressive strength, is considered as the dependent variable.

2. Statistical Dataset Analysis: The dataset is analyzed statistically by using Python programming tools, the assessment of the impact of each variable by using scatter plots and identifying the impacts of input variables in predicting the target variable (compressive strength).

3. Model Development: Creating Models by using different regression algorithms.

4. Iteration: Steps 2 and 3 are repeated until the obtained results show the most feasible outcomes.

5. Variable Impact Assessment: The effect of each variable is further analyzed using different diagrams and outputs from the ML models, particularly the R^2 score.

6. Experimental Validation: Experimental tests on relevant samples are conducted in accordance with the developed algorithm.

Fig. 1. MATEST Compressive Strenghth Testing Machine

Research results and discussion. The statistical summary (Table 1) obtained using Python programming tools, reveals that unlike conventional concrete – where, for example, higher cement content generally leads to increased compressive strength upto some levels – EPS concrete behaves differently. In EPS-modified concrete, each ingredient significantly affects the final properties, indicating the need for a specialized mix design algorithm that can achieve the desired strength without compromise.

Table 1

Statistical Summary

Variable Type	Ingredients	Count	Mean	Std	Min	25%	50%	75%	Max
Inputs	Cement, kg/m^3	125	431.169	85.9748	301	375	425	496	744
	Silica Fume, kg/m^3	125	22.0424	36.2721	0	0	0	40	127.23
	Water, kg/m^3	125	191.248	70.4769	104	152.67	175	180	390
	w/c	125	0.4396	0.11919	0.24	0.3	0.45	0.56	0.63
	Superplasticizer, kg/m^3	125	3.17788	2.92204	0	0	3.15	4.2	9.6
	Coarse Aggregate, kg/m^3	125	538.821	406.299	0	201	591	890	1224
	EPS, kg/m^3	125	119.738	187.713	0	6.06	13.9	189	905
	Average EPS Size, mm	125	2.0896	1.50198	0	0.8	2.25	2.6	5
	Fine Aggregate, kg/m^3	125	376.173	263.248	0	118	467	593	812
Output	28-Day Compressive Strength, MPa	125	21.786	16.8992	1.45	5.89	20.6	34.04	68.3

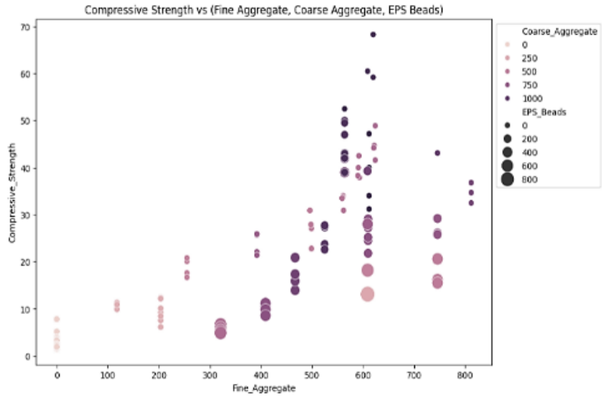

Fig. 2. Scatter Plots of EPS Content vs Compressive Strength

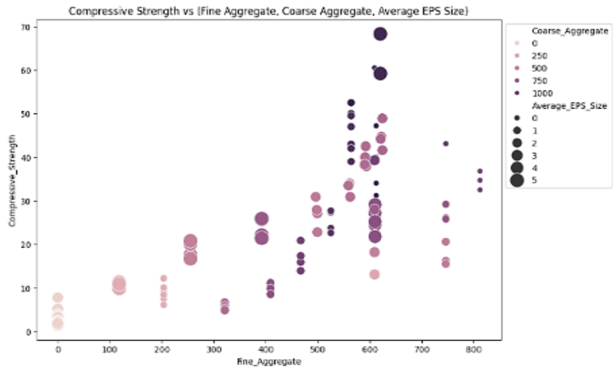

Fig. 3. Scatter Plots of EPS Size vs Compressive Strength

The scatter plots in Figure 2 and Figure 3 show that the relationship between the compressive strength and fine aggregate content, with color intensity and bubble sizes indicating the effects of coarse aggregate and EPS bead. It reveals that higher coarse aggregate correlates with increased compressive strength with moderate fine aggregate content. Moreover, it shows that the size and content of EPS beads significantly impact the compressive strength, with an optimal EPS volume and size of around 10% and 3-4mm is required to achieve a compressive strength of around 33 MPa. Based on this optimal EPS proportion and size, the corresponding mix ratio is determined to be 1:1.81:2.57. Beyond this range, further increases in EPS content or size lead to a decline in compressive strength.

To handle complex relationships in the dataset with high accuracy, three predictive ML Models: Gradient Boosting, Random Forest and XGBoost are used. This part of the study evaluates the predictive performance of these models by comparing their predictions. Scatter plot, representing the correlation between actual and predicted values, is obtained for each model by using Python programming tools. Primarily, the analysis is to assess the accuracy, reliability, and practical applicability of these models in real-world scenarios. By comparing their prediction performances, this study aims to highlight strengths and limitations, thereby guiding model selection for experimental setups.

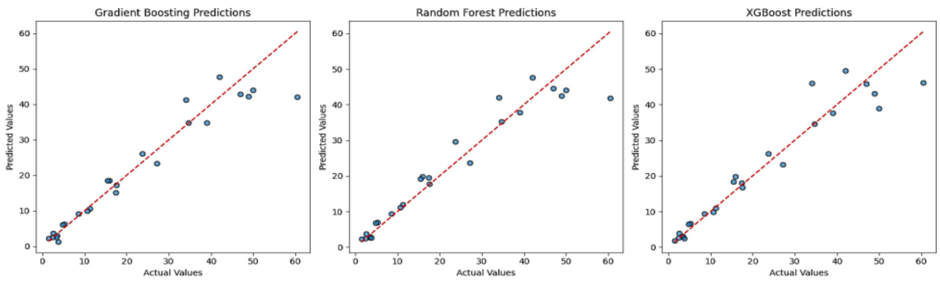

Fig. 4. Scatter plots of ML Models

As shown in Figure 4, all three models show good performance in which most points cluster around the red dashed lines. The predicted values that are obtained for all the three predictions used align closely with the actual values with slight deviation for some data points that are with higher actual values. Nevertheless, the performance of XGBoost regression has slightly more variance in predictions whereas gradient boosting and random forest regressions have relatively a strong predictive ability for this dataset. Generally, compared to XGBoost, Gradient Boosting and Random Forest seem slightly better aligned around the red lines. To accurately quantify the performance differences, further metrics such as R^2 Score, Mean Squared Error (MSE), and Mean Absolute Error (MAE) are needed. The value of each metric has been extracted by using the Python programming libraries and tabulated as follows in Table 2.

Table 2

Metrices to Quantify the Performance Differences

Model	MAE	MSE	RMSE	R^2 Score
Gradient Boosting	3.0737	23.7261	4.8709	0.9254
Random Forest	3.1157	24.793	4.9793	0.9221
XGBoost	3.0788	24.8197	4.9819	0.922

As indicated in Table 2 by low Mean Absolute Error (MAE), Mean Squared Error (MSE), and Root Mean Squared Error (RMSE), as well as high R^2 Scores, all the three models highlight strong performance in predictive accuracy. Nevertheless, Gradient Boosting achieving the best performance indicating superior predictive capacity for this dataset.

The experimental program, based on the developed algorithm, on the other hand examines the impact of varying EPS bead content on the compressive strength of concrete, four mix designs were prepared with each mix used constant quantities of cement (2828 g/m³), fine aggregate (5117 g/m³), and water (1330 g/m³), while the volume of coarse aggregate was progressively reduced to accommodate EPS at 0%, 10%, 20%, and 30%. As shown in Table 3, the control mix (MIX-I), containing no EPS, achieved the highest compressive strength of 41.75 MPa. The fresh concrete mix before the addition of EPS beads is shown in Fig 5. With the inclusion of 10% EPS beads (MIX-II), the compressive strength decreased to 33.23 MPa, representing the optimal balance between weight reduction and structural performance. Further increases in EPS content (MIX-III and MIX-IV) led to significant strength reductions, confirming that 10% EPS is the most effective proportion for maintaining sufficient mechanical properties while benefiting from the lightweight characteristics of EPS-modified concrete. The process of loading the samples into the compression testing machine is shown in Figure 6, failure cracking patterns in

Figure 7, and the digital readings of the compressive strength from the machine for each cube is presented as follows in Figure 8.

Table 3

Cubic Compressive Strength

MIX DESIGN	Cement (g/m^3)	Fine Aggregate (g/m^3)	Coarse Aggregate (g/m^3)	Water (g/m^3)	EPS Beads (10%)	Cubic Compressive Strength fcu' (MPa)
MIX-I	2828.00	5117.00	7328.00	1330.00	-	41.75
MIX-II	2828.00	5117.00	7254.72	1330.00	10	33.23
MIX-III	2828.00	5117.00	7109.63	1330.00	20	23.20
MIX-IV	2828.00	5117.00	6967.43	1330.00	30	16.86

Fig. 5. EPS concrete mix

Fig. 6. Loading the sample

Fig. 7. Crack pattern after loading

Fig. 8. Machine Reading

Conclusion. The results from the scatter plots and the experimental tests reinforce the idea that both the quantity and size of EPS beads are critical factors in affecting compressive strength and they're needed to be carefully optimized both in amount and size to attain the desired compressive strengths. The intricate interactions between fine aggregate, coarse aggregate, and EPS beads' size and proportion in influencing the compressive strength which can guide the optimization of material compositions for applications with specific requirements. This avoids an intensive mix trial and propose a simple mix design approach for EPS concrete. This study, depending on the developed scatter plots, reveals that by employing different mechanisms, it's possible to achieve the desired strength. The possible optimization strategies extracted from the scatter plots include: optimize the proportion of EPS beads while maintaining the desired strength, use a target proportion and balance the compressive strength and lightweight goals experimentally, for the perfect correlation between the EPS beads and its size, reduce the beads size while maintaining the proportion may help mitigate negative effects on compressive strength, increase the contents of the fine aggregate and that of coarse aggregate to offset the slight reduction in strength due to EPS beads, use w/c ratio adjustment, incorporation of superplasticizer or other admixtures to enhance the workability of the concrete and conduct an extensive material-based flexural and compressive strength tests to optimize the threshold for the EPS beads content so that the strength doesn't drop below the acceptable levels. This paper finally recommends the prioritization of optimizing coarse aggregate, fine aggregate, and water to cement ratio to maximize the compressive strength and to comprehensively investigate the negative effects of EPS beads on the strength, considering tradeoffs or threshold values, introducing different mitigation measures. To refine these strategies, a comprehensive empirical investigation with extended parameters must be conducted.

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КЕҢЕЙТІЛГЕН ПОЛИСТИРОЛДЫҢ БЕТОНДАҒЫ МӨЛШЕРІ МЕН КӨЛЕМІН МАШИНАЛЫҚ ОҚЫТУ ӘДІСТЕРІН ҚОЛДАНУ АРҚЫЛЫ СТОХАСТИКАЛЫҚ ОҢТАЙЛАНДЫРУ

Аңдатпа. Бұл мақалада бетон құрамына кеңейтілген полистиролды (EPS) енгізудің әсерін болжау бойынша машиналық оқыту алгоритмдерін пайдалану арқылы жүргізілген зерттеу ұсынылған. Халықаралық беделді журналдардан алынған 125 үлгіден тұратын деректер жиынтығы Python құралдарының көмегімен талданды. Зерттеудің негізгі мақсаты – бетон қоспаларындағы EPS түйіршіктерінің көлемі мен мөлшерін 28 тәуліктік сығылу беріктігін төмендетпей оңтайландыруға арналған сенімді алгоритмді әзірлеу. Gradient Boosting Regression, Random Forest Regression және XGBoost модельдері қолданылып, MAE, MSE, RMSE және R^2 көрсеткіштері бойынша бағаланды, соның негізінде ең үздік болжамдық модель таңдалды. Жаңадан жасалған алгоритмге сүйене отырып, тәжірибелік сынақ жүргізілді және алынған нәтижелер болжанған мәндермен жоғары сәйкестік көрсетті, тек аздаған айырмашылықтар байқалды. Зерттеу EPS түйіршіктері мен бетонның басқа компоненттерінің өзара әрекеттесуін тереңірек түсіну үшін қосымша тәжірибелік зерттеулер жүргізуді ұсынады. Сондай-ақ, бетон құрамын жобалауда EPS-ті тиімді біріктіру үшін пәнаралық тәсілдердің және тәуекелді азайту стратегияларының маңыздылығы атап өтіледі.

Тірек сөздер: бетон, сығылу беріктігі, машиналық оқыту, кеңейтілген полистирол (EPS), Python.

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СТОХАСТИЧЕСКАЯ ОПТИМИЗАЦИЯ РАЗМЕРА И ПРОПОРЦИИ ПЕНОПОЛИСТИРОЛА В БЕТОНЕ С ИСПОЛЬЗОВАНИЕМ МАШИННОГО ОБУЧЕНИЯ

Аннотация. В статье представлено исследование прогнозирования влияния включения EPS в бетон с использованием алгоритмов МО. Набор данных из 125 образцов из авторитетных международных журналов был проанализирован с помощью инструментов Python. Основной целью данного исследования является разработка надежного алгоритма для оптимизации размера и пропорций гранул EPS в бетонных смесях без ущерба для прочности на сжатие через 28 дней. Модели Gradient Boosting Regression, Random Forest Regression и XGBoost были применены и оценены с использованием MAE, MSE, RMSE и R^2 оценки для выбора наилучшей прогностической модели. На основе этого недавно разработанного алгоритма был проведен экспериментальный тест, и результаты близко соответствовали прогнозируемым значениям с небольшим различием. В исследовании рекомендуются дальнейшие экспериментальные исследования для понимания взаимодействия между гранулами EPS и другими ингредиентами бетона. Также подчеркивается важность междисциплинарных подходов и стратегий смягчения для лучшей интеграции EPS в проектирование бетона.

Ключевые слова: бетон, прочность на сжатие, машинное обучение, пенополистирол, Python.