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Application of MATLAB-assisted Ridge Regression in Weight Reduction and Environmental Protection of Glass Bead Concrete

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Abstract

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This study utilizes MATLAB to develop a Ridge regression prediction model, aimed at assessing the impact of incorporating vitrified microbead insulation sand into concrete on both weight reduction and environmental performance. Empirical findings indicate that substituting 20% of the manufactured sand with vitrified microbead insulation sand in C25 concrete reduces the concrete's weight from 24.98 kg to 24.68 kg, achieving a 0.12% reduction. Concurrently, the compressive strength is significantly enhanced, increasing from 38.5 MPa to 40.3 MPa, indicating a notable improvement in material performance. The weight of the model-predicted concrete is 24.8873 kg, closely aligning with the actual experimental data, thereby affirming the accuracy and reliability of the Ridge regression model. The findings of this study provide robust scientific evidence supporting the lightweight design and sustainable application of concrete materials, highlighting the extensive potential of vitrified microbeads in construction engineering.

Keywords: MATLAB, Ridge regression, concrete lightweighting, vitrified microbeads, environmental performance

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Introduction

Glass beads, an inorganic glassy mineral material made from slag such as silicon and aluminum that is melted at high temperatures and rapidly cooled, have stable physicochemical properties and excel in thermal insulation, fire protection, sound absorption, and lightweight. As a result, they are widely used in various fields such as construction, chemical engineering, and aerospace (Li, 2018; Wu et al., 2023). In the construction industry, glass beads are used as lightweight aggregate to enhance the flowability and self-compressive strength of the sand, reduce the shrinkage of the material, improve the comprehensive performance of the product, and at the same time, effectively reduce production costs (Azevedo, 2024; Hou et al., 2023; Li et al., 2020).

Wu Yuan’s research indicated that mixing 20%-40% glass beads into concrete can significantly enhance its mechanical properties and effectively reduce its thermal conductivity, showing substantial energy-saving advantages (Wu, 2021). Through orthogonal experiments, Wang Xuan optimized the proportions of fly ash, silica fume, and glass beads in concrete to obtain the best combination of cubic compressive strength, splitting tensile strength, and flexural strength, which further demonstrated the significant advantages of glass bead concrete in energy saving (Wang, 2022). Additionally, other studies, such as the seismic performance analysis by Zhu Baohua and the shear wall tests by Gao Yuxuan, verified the potential of glass bead concrete in energy-saving and seismic applications, showing its promise as a sustainable building material (Gao et al., 2018; Zhu & Han, 2018).

However, relatively few studies have been conducted on the use of glass beads insulating sand for replacing mechanism sand to reduce the deadweight of concrete. Exploring this area could further enhance the market application value of glass beads. In order to summarize and deepen these studies, this paper investigated the effectiveness of glass bead insulating sand in replacing concrete with machine-made sand through experimental analysis, ultimately producing glass bead concrete with optimized properties. Using Matlab to construct a Ridge regression prediction model (Zeng & Lü, 2001), this study verified the impact of manufactured sand weight, the volume of glass bead insulation sand substitution, and the amount of water-reducing agent on the concrete weight. The aim of this research is to provide theoretical support and practical guidance for the application of glass bead concrete in future construction projects by optimizing concrete design, which will help its promotion and application in the construction industry.

Literature Review

With the acceleration of urbanization and the increasing energy consumption in buildings, developing energy-efficient and environmentally friendly building materials has become one of the core tasks in the construction industry. As a new type of lightweight material, glass beads have shown great potential in enhancing concrete performance due to their excellent insulation properties and lightweight characteristics (Li et al., 2017). Hou et al. (2023) found that using glassy fly ash microbeads as a concrete admixture can significantly improve its microstructure and enhance crack resistance and compactness. The addition of this material notably reduced the heat of hydration released in concrete, thereby decreasing the risk of temperature-induced cracking and improving the stability and durability of the structure (Hou et al., 2023). This was further verified by Wu et al. (2023). The highly doped slag fly ash glass bead insulating sand walls had low thermal conductivity and excellent thermal insulation performance, achieving an energy-saving rate of over 50%, which strongly indicated the significant potential of glass beads in building energy-saving (Wu et al., 2023). Through orthogonal experiments, Liu et al. (2023) analyzed the impact of straw powder, polypropylene fibers, and glass beads on the thermal conductivity of insulation concrete. The results showed that glass beads can effectively extend the heat transfer path and enhance thermal insulation effect. In addition, the concrete crack width calculation method developed by Liu was using Matlab showed higher accuracy and efficiency than the traditional method, providing an innovative technical approach to crack detection (Liu et al., 2022).

In conclusion, glass beads exhibit significant potential in enhancing the thermal performance of concrete, improving structural durability, and reducing weight. Future research should focus on exploring their performance under various environmental conditions and the possibility of combining them with other innovative materials. These studies not only highlight the broad prospects of glass beads as an innovative material in construction engineering but also provide new perspectives and methods for developing lightweight and efficient building materials.

Materials and Experiment

Materials and Parameters

Cement: P•O42.5, sulfur trioxide content 2.44%, 3-day compressive strength 27.3 MPa. Glass beads Insulation Sand: JFGN inorganic insulation sand, dry density 256 kg/m³, linear shrinkage rate 0.085%.

Fly Ash: Fineness 45 μm, moisture content 0.1%.

Water-Reducing Agent: Polyhydroxy acid-based high-performance water-reducing agent, water release rate 57%, oxygen content 2.4%.

Manufactured Sand: Fineness modulus 2.6, apparent density 2602 kg/m³.

Crushed Stone: Particle size 5–10 mm, apparent density 1594 kg/m³.

Water: Potable water.

Mix Design

Based on China's Specification for Mix Proportion Design of Ordinary Concrete (JGJ55-2011), this experiment was designed for the performance of C25 grade normal concrete (NC) (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2011). The same design mix was also referred for the preparation of Glazed Hollow Bead Concrete (GHBC). During the experiment, glass bead insulation sand was used to replace the volume of manufactured sand aggregate in normal concrete, with replacement ratios set at 0%, 15%, 20%, and 25%. The experimental mix proportions are shown in Table 1.

Table 1 Experimental Mix ratios for C25 Normal Concrete and Glazed Hollow Bead Concrete

Concrete	Water-Cement Ratio (W/C)	Cement /kg (y)	Crushed Stone/kg	Manufactured Sand/kg (x_1)	Fly Ash /kg	Glass bead Insulation Sand Replacement Ratio in NC /% (x_2)	Water-Reducing Agent /kg (x_3)	Water /kg
NC	0.50	7.735	33.705	33.75	3.325	0	0.21000	5.530
GHBC15	0.50	7.735	33.705	29.25	3.335	15	0.21545	5.530
GHBC20	0.50	7.735	33.705	27.56	3.335	20	0.21686	5.530
GHBC25	0.50	7.735	33.705	25.92	3.335	25	0.21328	5.530

Note: In the experimental mix proportion table, the independent variables include the weight of manufactured sand (x_1), the replacement ratio of glass bead sand(x_2), and the weight of the water-reducing agent (x_3), while the dependent variable is the weight of the cement (y)

Testing Methods

This study employed the cement-coated sand method (Hu, 2021) to prepare Glazed Hollow Bead Concrete (GHBC). Based on the design mix ratios, precise measurements of cement, glass bead insulation sand, manufactured sand, coarse aggregate, and fly ash were taken. The amounts of water-reducing agent and water were adjusted according to the cement ratio and the desired slump. Firstly, the weighed manufactured sand, coarse aggregate, fly ash, and glass bead insulation sand were mixed with some water. Secondly, cement and the remaining water were added and mixed until evenly distributed. Thirdly, the water-reducing agent was combined with part of the water to form a solution, which was slowly added to the mixer, gradually incorporating the remaining water to achieve a uniform concrete texture. Then, a portion of the mixed concrete was taken for a slump test, and adjustments to the water or water-reducing agent were made as needed to achieve the desired slump. Standard 150mm cubic test molds were selected (Hou et al., 2023), and a vibrating plate was used to remove air bubbles and compact the concrete. After the final setting, the specimens were placed in a standard curing room for standard curing. At 7 and 28 days of curing, the weight, load, and strength of the specimens were tested to evaluate whether they met the design requirements. The GHBC experiments are illustrated in Figure 1.

Figure 1 Concrete Mixing, Specimen Weight and Concrete Performance Testing

Results and Discussion

Experimental Results

In the experiment, glass bead insulation sand was mixed into C25 normal concrete and Glazed Hollow Bead Concrete (GHBC) at different ratios. The results showed improvements in slump, spread, specimen weight, failure load, and compressive strength, with performance parameters detailed in Table 2. Specifically, the specimen weight changed as the volume of manufactured sand replaced by glass bead insulation sand increased: with a 15% replacement ratio, the weight decreased by 0.04%; with a 20% replacement ratio, the weight decreased by 0.12%; however, with a 25% replacement ratio, the weight increased by 0.72%. This indicates that mixing an appropriate amount of glass bead sand can effectively reduce the weight of the concrete. To analyze the impact of different replacement ratios on concrete weight more scientifically, this study utilizes Matlab to develop a Ridge regression prediction model, verifying the feasibility and effectiveness of reducing concrete weight by substituting manufactured sand with glass bead insulation sand.

Table 2 Performance Parameters of C25 Normal Concrete and Glazed Hollow Bead Concrete

Concrete	Slump /mm	Spread /mm	Concrete Weight f_{mg}/kg	Failure Load f_{Pf}/KN 28d	Compressive Strength $f_{cu,o}$/Mpa 28d
NC	145	315	24.98	865.167	38.5
GHBC15	200	269	24.99	999.967	44.4
GHBC20	195	283	24.68	908.167	40.3
GHBC25	205	248	25.17	913.167	40.6

Note: In the experimental results table, the dependent variables include the concrete weight, 28-day compressive strength, and others.

MATLAB Ridge Regression Analysis

To study the impact of the volume of glass bead sand replacing manufactured sand in concrete, as well as the weight of manufactured sand and water-reducing agent on the weight of concrete, a Ridge regression prediction model was designed in this study using Matlab. Ridge regression achieves parameter shrinkage through regularization, specifically by adding a penalty term to the loss function (least squares method), as shown in Equation (1):

$$L(\beta) = \sum_{i=1}^{n}(y_i - \sum_{j=1}^{p} x_{ij}\beta_j)^2 + \lambda \sum_{j=1}^{p} \beta_j^2$$

$$L(\beta) = \sum_{i=1}^{n}(y_i - \beta_0 - \sum_{j=1}^{p} \beta_j x_{ij})^2 + \lambda \sum_{j=1}^{p} \beta_j^2 \quad \text{....................(1)}$$

In this equation, λ is the regularization parameter, where a larger λ value imposes a stronger constraint on the model parameters, bringing them closer to zero, thereby reducing the likelihood of overfitting. p represents the number of features or independent variables. As λ increases, the penalty term becomes more significant, leading to greater compression of the model coefficients.

After incorporating the regularization term, the linear regression equation for Ridge regression effectively reduces the complexity of the model, particularly in the presence of multicollinearity issues, thereby enhancing the generalization capability of the model. Before applying Ridge regression, the input variables have to be standardized to eliminate the influence of different dimensions. The standardization formula is shown in Equation (2):

$$z = \frac{x-\mu}{\sigma} \quad \text{......................(2)}$$

Where:

- X is the independent variable, represents the standardized values of the independent variables, including *WmsA*, *VrepB*, and *WadC*.;
- μ is its mean;
- σ is its standard deviation.

By introducing the regularization term into the regression equation, Ridge regression can effectively address potential overfitting issues that may arise in ordinary least squares (OLS) regression, so as to improve the predictive accuracy for new data. The regression prediction model is expressed as follows:

$$\hat{Y} = b_o + b_1 Z_{W_{msA}} + b_2 Z_{W_{repB}} + b_3 Z_{W_{adC}} \quad \text{..................................(3)}$$

Where:

Z_{WmsA} : Standardized weight of manufactured sand;

Z_{VrepB} : Standardized replacement ratio of vitrified microbead sand;

Z_{WadC} : Standardized additional parameter.

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Y : represents the actual measured weight of the concrete.

$\hat{y}$: represents the concrete weight predicted by the Ridge Regression model.

By introducing the λ term, Ridge regression effectively mitigates the potential overfitting problem associated with ordinary least squares (OLS) regression and enhances the prediction of unknown data. Using this model and its computational principles, it is possible to accurately predict the weight of concrete based on the new decision variables and to gain a deeper understanding of the statistical reasoning behind the model

Based on the data related to the replacement of manufactured sand with glass bead sand from Table 1 and 2, Matlab was used to perform Ridge regression prediction. The regression coefficients obtained from the model were: an intercept of 24.9550, a manufactured sand weight coefficient of -0.0421, a glass bead replacement ratio coefficient of 0.0438, and a water-reducing agent weight coefficient of -0.1271. The predicted values were 25.0023, 24.8873, 24.8687, and 25.0617 respectively. These results demonstrate the linear impact of the Ridge regression coefficients on the target variable and indicate that the model effectively captures trends. Overall, the model's predictions are close to the actual values, as shown in Figures 1. The residuals are generally small, indicating a good fitting effect, as illustrated in Figure 1. Meanwhile, the two-dimensional field plot analysis reveals that the interaction effect between the weight of manufactured sand and the replacement ratio of glass bead sand is relatively complex, as shown in figure 1, which highlights the need for careful selection of appropriate proportions in concrete mix design to achieve optimal performance.

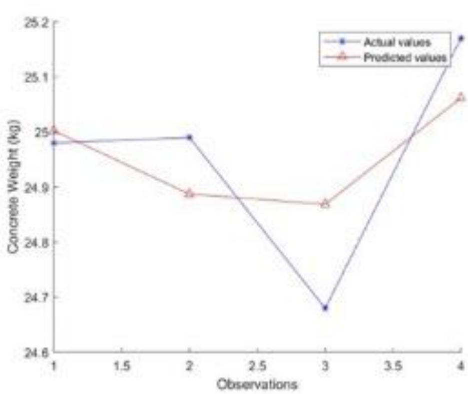

Figure 2 Comparison of Actual and Predicted Values

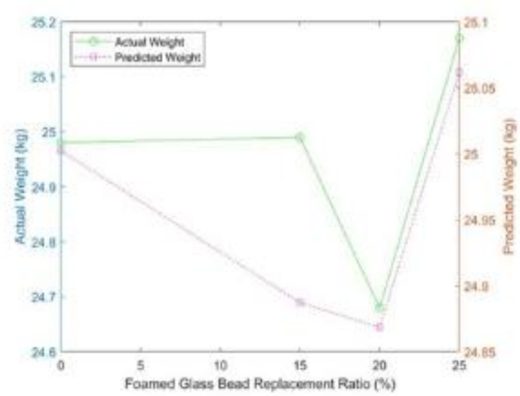

Figure 3 Actual vs. Predicted Weight with Multi-Y Axis

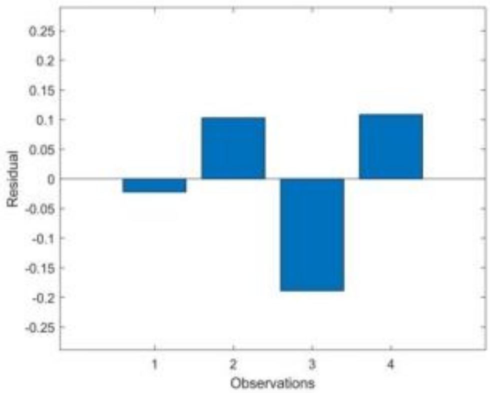

Figure 4 Residuals Plot

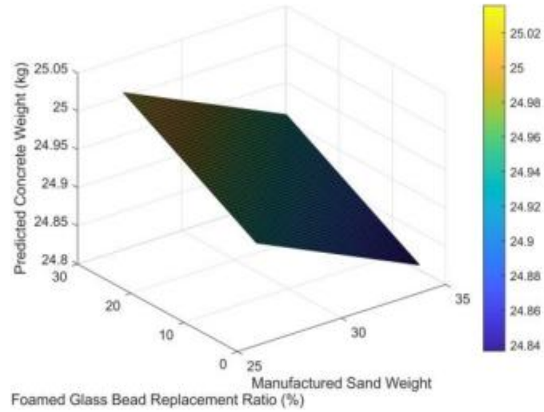

Figure 5 Two-Dimensional Field Plot

In summary, the experiment demonstrates that when glass bead insulation sand is mixed into C25 normal concrete and Glazed Hollow Bead Concrete (GHBC) at different ratios, the performance parameters, such as slump, spread, specimen weight, failure load, and compressive strength, show improvement. Notably, with a 20% replacement ratio, the concrete weight decreased by 0.12%, from 24.98 kg to 24.68 kg, while the compressive strength increased to 40.3 MPa, a significant improvement compared to the 38.5 MPa of normal concrete. Ridge regression model analysis using Matlab yielded the following regression coefficients: an intercept of 24.9550, a manufactured sand weight coefficient of -0.0421, a glass bead insulation sand replacement ratio coefficient of 0.0438, and a water-reducing agent weight coefficient of -0.1271. The predicted concrete weight was 24.8873, which closely matched the actual data, indicating that the model had a good fit. The study shows that a 20% replacement ratio not only effectively reduces the weight of C25 normal concrete but also improves its mechanical properties, highlighting the significant advantages of using glass bead sand in concrete.

Conclusions and Future Directions

The experimental study indicates that with 20% glass bead insulation sand replacement, the performance of C25 concrete is significantly improved. Specifically, the concrete weight decreased from 24.98 kg to 24.68 kg, a reduction of 0.12%, demonstrating the significant effect of glass bead insulation sand in weight reduction. Meanwhile, the compressive strength increased from 38.5 MPa to 40.3 MPa, indicating that it not only reduces weight but also enhances strength.

The analysis of Matlab's Ridge regression model confirmed the effectiveness of substituting glass bead sand for manufactured sand in reducing weight and increasing strength. Model predictions are highly consistent with the actual data, with small residuals and excellent fitting results.

Furthermore, the reduced concrete weight cuts down construction and transportation energy consumption and carbon emissions. By replacing natural sand and gravel with glass bead insulation sand, natural resources can be conserved, environmental damage will be reduced, and the excellent thermal insulation properties can also improve building energy efficiency and reduce operational costs.

In conclusion, glass bead thermal insulation sand shows a broad prospect in construction projects, not only to optimize the performance of concrete, but also to bring significant social and economic benefits, with great value of promotion and application.

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