USING MACHINE LEARNING TO PREDICT THE MECHANICAL PROPERTIES OF PET FIBER-REINFORCED CONCRETE

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Fiber-reinforced concrete enhances structural integrity by improving post-cracking behavior and ductility, yet traditional fibers can be costly and have a significant environmental impact. Recently, polyethylene terephthalate (PET) fiber, derived from recycled plastic bottles, has been used as a reinforcing material in concrete to enhance its mechanical properties. Utilizing advanced machine learning algorithms, this research analyzes a comprehensive dataset collected from existing literature on the mechanical properties of PET fiber-reinforced concrete (PFRC), including concrete density, water-to-binder ratio, fine and coarse aggregates, and fiber parameters such as volume fraction and aspect ratio of PET fibers. Through the application of Polynomial Regression, Exponential Gaussian Process Regression (GPR), and Cubic Support Vector Machine (SVM) models, the study effectively predicts PFRC’s mechanical behavior, showcasing high R^2 values indicating the models’ predictive strength: 0.93 for compressive, 0.92 for flexural, and 0.92 for tensile properties. This investigation highlights the exceptional accuracy of Exponential GPR and Cubic SVM models in capturing complex, non-linear relationships within the material, demonstrating machine learning’s capability to advance the sustainable development of construction materials. This study provides significant insights into optimizing the use of recycled fibers for concrete reinforcement.

Keywords: Polyethylene terephthalate, Flexural strength, Tensile strength, Polynomial regression, Gaussian process regression, Support vector machine.

1 INTRODUCTION

The construction industry progressively embraces innovative solutions to the dual challenges of enhancing construction material performance and addressing environmental concerns. Fiber-reinforced concrete (FRC), particularly when integrated with fibers from recycled polyethylene terephthalate (PET) bottles, represents a significant leap forward. This approach improves the tensile strength, ductility, and crack resistance of concrete and offers a viable route to address the problem of global plastic waste (Khalid et al. 2018). Furthermore, by integrating recycled PET fibers, this initiative aligns with broader sustainability goals, transforming waste into valuable construction materials and contributing to a circular economy in the construction sector.

This study is situated at the intersection of advanced material science and environmental sustainability, with a specific focus on utilizing machine learning (ML) to predict the mechanical properties of PET fiber-reinforced concrete (PFRC) across diverse mix designs. This research seeks to uncover the relationships between the composition of PFRC and its mechanical outcomes using ML algorithms to analyze carefully compiled datasets. Central to this investigation is the application of the following various regression models: polynomial, Gaussian Process Regression...
(GPR), and Support Vector Machine (SVM), each chosen for their potential to offer accurate predictions of PFRC’s mechanical properties (Kumar et al. 2022). This methodological diversity allows for a comprehensive evaluation of each model’s effectiveness, setting the stage for advancements in the precision of material property prediction. Through this detailed analysis, the study aims to improve how we predict material behavior in construction, helping make PET FRC mixes better for building durable structures. This effort seeks to use PET FRC in building projects better and shows how important machine learning is in developing new ways to use materials in construction.

2 METHODOLOGY

2.1 Data Collection and Statistical Analysis

The dataset used in this study was carefully collected from numerous scholarly articles, resulting in a comprehensive set of 100 observations relevant to the mechanical properties of PET fiber-reinforced concrete (PFRC) (Ochi et al. 2007, Prahallada and Prakash 2013, Nibudey et al. 2013, Sharma et al. 2014, Khalid et al. (2018), Al-Hadithi and Abbass 2018, Adnan and Dawood 2020, Anandan and Alsubih 2021, Mohammed and Mohammed 2021). This dataset is designed to cover all the essential features that influence the properties of PFRC, including density, water-to-binder ratio, fine and coarse aggregates, fiber volume, and fiber aspect ratio. The concrete mix designs used in the literature are diverse and provide a broad analytical base for the study. It is essential to systematically examine the statistical composition of the dataset to comprehend the data variance and central tendencies comprehensively. Table 1 summarizes the minimum, maximum, mean, and standard deviation for each parameter in the dataset. This information serves as a reliable basis in the data preprocessing stage.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>kg/m³</td>
<td>2267</td>
<td>2541</td>
<td>2400</td>
<td>81</td>
</tr>
<tr>
<td>W/B ratio</td>
<td>-</td>
<td>0.41</td>
<td>0.65</td>
<td>0.506</td>
<td>0.0568</td>
</tr>
<tr>
<td>Fine aggregates</td>
<td>kg</td>
<td>553</td>
<td>980</td>
<td>725</td>
<td>154.8</td>
</tr>
<tr>
<td>Coarse aggregates</td>
<td>kg</td>
<td>743</td>
<td>1398</td>
<td>1062</td>
<td>199</td>
</tr>
<tr>
<td>Fiber volume</td>
<td>%</td>
<td>0</td>
<td>3</td>
<td>0.722</td>
<td>0.732</td>
</tr>
<tr>
<td>Fiber aspect ratio</td>
<td>-</td>
<td>6</td>
<td>122</td>
<td>40.7</td>
<td>26.1</td>
</tr>
<tr>
<td>Compressive strength</td>
<td>MPa</td>
<td>24.44</td>
<td>53.85</td>
<td>34.3</td>
<td>5.59</td>
</tr>
<tr>
<td>Flexural strength</td>
<td>MPa</td>
<td>3.72</td>
<td>6.55</td>
<td>4.84</td>
<td>0.75</td>
</tr>
<tr>
<td>Tensile strength</td>
<td>MPa</td>
<td>2.28</td>
<td>4.18</td>
<td>3.26</td>
<td>0.43</td>
</tr>
</tbody>
</table>

During the preprocessing phase, a suite of visual tools, including histograms, scatter plots, box plots, and correlation matrices, were employed to deepen the understanding of the data’s structure and the interrelationships between features. These instruments were crucial in observing patterns and differences, aiding in evaluating feature significance and distribution uniformity. This analytical inspection ensured the dataset’s representativeness and readiness for predictive modeling. Enhanced visual analyses provided additional insights into each variable’s variability and central tendencies, informing the subsequent data-cleaning steps. The dataset’s accuracy was enhanced by identifying and removing outliers during an initial analysis. Normalization procedures were then applied to achieve consistency across feature scales, optimally conditioning the data for the application of advanced regression models. The precise preparation of data improves the
model’s capability to reveal the complex connections present in the data. This helps to make robust forecasts regarding the mechanical characteristics of PET fiber-reinforced concrete.

2.2 Machine Learning Models

This research aims to use machine learning to predict the mechanical behavior of PET fiber-reinforced concrete (PFRC) by employing three advanced regression models: Polynomial Regression, Exponential Gaussian Process Regression (GPR), and Cubic Support Vector Machine (SVM). Each model brings a unique perspective to understanding and anticipating the mechanical behaviors of PET fiber-reinforced concrete (PFRC). The dataset was split into 80% for training the models and 20% for testing the model’s predictive effectiveness on new data. This separation is crucial to ensure that the models can learn from the existing data and apply that learning to new datasets.

In the mechanical analysis of PET fiber-reinforced concrete (PFRC), a second-degree polynomial regression model is utilized to predict the material’s non-linear behavior. This model surpasses linear regression, detailing the complex relationship between PFRC composition and mechanical properties. Optimization is central to the model’s efficacy, where the coefficients are adjusted to minimize the residual sum of squares (RSS), improving the accuracy of predictions. Using gradient descent refines these coefficients, enabling the model to closely align predictions with observed data, thereby providing a reliable method for predicting PFRC’s mechanical strengths.

Exponential Gaussian Process Regression (GPR) is applied to predict the mechanical properties of PET fiber-reinforced concrete (PFRC), harnessing its strength in uncovering complex, non-linear relationships within the material. This advanced model utilizes Gaussian processes for a probabilistic regression approach, where predictions encompass distributions that reflect uncertainty, enhancing prediction reliability. The selection of an exponential kernel is important to effectively model the decrease in correlation as input distances increase, thus ensuring the model’s sensitivity to the complexity of the data. This application of exponential GPR enriches the analysis by providing detailed insights into PFRC’s behavior, utilizing probabilistic predictions to offer a comprehensive understanding of material performance.

Cubic Support Vector Machine (SVM) Regression is deployed to model the mechanical properties of PET fiber-reinforced concrete (PFRC), which is good at managing high-dimensional data with a non-linear approach. Founded on structural risk minimization, it employs a cubic kernel to uncover non-linear patterns effectively, enhancing data separability in a higher-dimensional space. The model aims to construct an optimal fit within a specific tolerance margin while minimizing complexity, optimizing a dual objective function that maximizes the separation between data points and the decision boundary and penalizes outliers. This balance ensures Cubic SVM remains a robust tool for accurately forecasting PFRC’s complex mechanical behaviors.

3 RESULTS AND DISCUSSION

3.1 Compressive Strength of PFRC

This research assessed the predictive power of compressive strength in PET fiber-reinforced concrete (PFRC) through a suite of regression models, using $R^2$ and RMSE metrics for both training and testing to gauge prediction accuracy. The second-degree polynomial regression model showcased considerable predictive strength, with $R^2$ values of 0.92 in training and 0.89 in testing and RMSEs of 1.44 and 1.71, respectively, indicating a strong alignment with actual compressive
strengths despite a minor performance dip in testing due to data complexity. This suggests that quadratic relationships within the selected features critically influence compressive strength.

Meanwhile, the Exponential GPR model surpassed the polynomial model with R² values of 0.96 and 0.91 and lower RMSEs of 1.04 and 1.21. This shows how well it can understand the material’s behaviors using its probabilistic method. The Cubic SVM model emerged as the most accurate, navigating high-dimensional relationships to achieve the highest R² scores of 0.97 and 0.93 and the lowest RMSEs of 0.94 and 1.04, underscoring its efficacy in predicting compressive strength.

In sum, while all models demonstrated notable predictive performances, the Cubic SVM model’s precision distinctly positioned it as a powerful tool for accurate compressive strength estimation in PFRC. A comparative plot in Fig. 1 visually underscores this, representing the correlation between actual and predicted strengths across models and reinforcing the discussion on model reliability and accuracy.

![Fig. 1. Actual vs predicted compressive strength from Polynomial, GPR, and SVM models.](image)

### 3.2 Flexural Strength of PFRC

In this segment, the investigation extends to the predictive analysis of flexural strength in PET fiber-reinforced concrete (PFRC). It employs the same set of regression models and analyzes their efficacy through R² and RMSE metrics during the training and testing phases. The polynomial second-degree model revealed a moderate predictive ability, with R² values of 0.67 for training and 0.75 for testing, alongside RMSEs of 0.38 and 0.23, respectively, suggesting a decent model fit and a somewhat variable correlation with the actual flexural strengths. The exponential GPR model, however, displayed outstanding predictive performance, achieving R² scores of 0.98 in training and 0.92 in testing, complemented by notably low RMSEs of 0.09 and 0.16. This excellence underscores the model’s strength in leveraging its probabilistic nature to accurately capture the complex, non-linear relationships influencing PFRC’s flexural strength.

The cubic SVM model demonstrated strong accuracy, with consistent RMSEs of 0.17 and R² values of 0.93 and 0.91 for the training and testing phases, respectively. The results highlight the unique capabilities of each regression model in predicting flexural strength, with the exponential GPR model performing exceptionally well. A comparative plot in Fig. 2 visually confirms the analysis and advances the understanding of PFRC through different machine-learning models.
3.3 Tensile Strength of PFRC

In assessing tensile strength for PET fiber-reinforced concrete (PFRC), this study utilized regression models to evaluate predictive accuracy, focusing on $R^2$ and RMSE metrics. The polynomial model demonstrated capability with $R^2$ values of 0.84 and 0.82 and RMSEs of 0.16 and 0.20 for training and testing, albeit showing some limitations with complex data. The exponential model outperformed with $R^2$ of 0.94 and 0.92 and RMSEs consistently at 0.11, proving adept at unveiling non-linear relationships. The cubic model, with $R^2$ of 0.95 and 0.90 and RMSEs of 0.10 and 0.15, emerged as the most accurate, skillfully navigating high-dimensional complexities.

These findings emphasize the exponential and cubic models’ effectiveness in accurately predicting tensile strength. A comparison in Fig. 3 visually showcases the actual versus predicted tensile strengths, underscoring the models’ dependability. This research enriches our insight into PFRC’s tensile attributes and highlights machine learning’s essential contribution to material science advancement.

4 CONCLUSIONS

This investigation into PET fiber-reinforced concrete (PFRC) underscores the significant impact of machine learning on accurately predicting the material’s mechanical properties, with a particular emphasis on sustainable materials like PFRC. The study highlights the exceptional performance of Exponential Gaussian Process Regression (GPR) and Cubic Support Vector Machine (SVM) models in decoding the complex, non-linear relationships affecting PFRC’s compressive, flexural,
and tensile strengths. These advancements demonstrate machine learning’s crucial role in advancing construction materials technology and the importance of integrating recycled materials for sustainable construction solutions. The research affirms the potential of machine learning to enhance the design and application of new sustainable construction materials. It lays a foundational step toward a more informed and sustainable approach to construction material innovation. By providing accurate predictions of innovative materials like PFRC, machine learning facilitates the development of durable, eco-friendly construction materials.

References


