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RESEARCH ARTICLE

Material Performance Evaluation of Cinder Based Light Weight Concrete with Micro-reinforcement

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Abstract

Objectives: The present work examines the viability of using industrial solid waste, like cinder, to create lightweight aggregate concrete. Utilizing cinder aggregate as a substitute material for coarse aggregate in producing concrete not only helps in the conservation of natural resource but also provides a feasible solution for solid waste management. **Method:** The mechanical characteristics of cinder based lightweight concrete were improved by the inclusion of polypropylene fibre as micro-reinforcement, in volume proportions of 0.1%, 0.2%, 0.3%, and 0.4%. The laboratory tests that were conducted on the polypropylene fibre reinforced cinder based lightweight concrete included compressive strength test on cube specimen and cylinder specimen, flexural strength test on prism specimen and modulus of elasticity test on cylinder specimen. **Findings:** The findings show that cinder aggregate can be satisfactorily utilized as an alternate material to coarse aggregate in the production of lightweight concrete. It has been found that 0.3% of polypropylene fibre was the ideal dosage of micro-reinforcement that can be incorporated in lightweight concrete. **Novelty**: Further, a multiple linear regression (MLR) model was suggested to evaluate the performance parameters of the fibre-reinforced lightweight concrete, providing an alternative to the time and material consuming experimental works. Scatter plots and Statistical indicators such as R^2, RMSE and MAPE indicated that the model demonstrated a strong correlation between the predicted values and the experimental results.

Keywords: Cinder aggregate; Lightweight concrete; Mechanical characteristics; Micro reinforcement; Regression model

1 Introduction

Current urban growth and infrastructural developments have prompted researchers to investigate and apply lightweight concrete with higher strength and durability while keeping sustainability in mind[1]. Lightweight concretes can be made by substituting lightweight aggregates for conventional coarse aggregates. Finding the right aggregate for the lightweight concrete, which includes expanded clay, perlite, vermiculite, pumice, scoria, recycled plastic aggregates etc, is a challenging task[2]. Cinder aggregate, a slag material obtained from the steel and iron industries, is a lightweight aggregate that has recently gained popularity. Using cinder aggregate in place of normal coarse aggregate not only saves money but also reduces coarse aggregate consumption, preserving natural resources.

Concrete is a brittle material that lacks ductility and has a low tensile strength. Fibres added to concrete help partially alleviate these drawbacks[3]. Polypropylene fibres are recently developed chemical fibres that improve the tensile strength, fatigue strength and flexural strength of the concrete. Concrete with fibre reinforcement is used extensively in the construction of pavement, floors of industries, long span bridges, prefabricated elements, machine foundations, safety vaults and so on.

The strength and durability properties of concrete make it a versatile material which is inevitable in the construction sector. The concrete characteristics are highly dependent on its constituents, which makes the behavior prediction an intricate process. Traditionally, statistical and empirical models were used in the prediction of concrete strength values. With the emergence of a new class of technology researchers are now motivated to use artificial intelligence in developing models to predict the concrete strength. Multiple Linear Regression (MLR), a mathematical free model, has been presented as a method for predicting the behaviour of concrete, which eliminates the need for experimentation.

Karthika et al.[4] conducted a study on the lightweight concrete prepared using pumice aggregate as coarse aggregate in volume proportions of 50%, 80% & 100%. Several destructive and non-destructive tests were conducted for assessing the performance of the lightweight concrete. It was found that the compressive strength of the lightweight concrete decreased when the replacement of conventional aggregate by pumice aggregate was beyond 50%. Also the authors suggested the use of the pumice based lightweight aggregate for non-load bearing applications and in earthquake resistance structures. Atyia et al.[5] investigated the effect of (CCB) crushed clay bricks as a replacement material for cement, fine aggregate and coarse aggregate by analysing the hardened properties, mechanical behaviour and microstructure characteristics of the concrete. The experimental tests were carried out for the determination of slump, hardened density, ultrasonic pulse velocity, compressive strength, porosity, thermal conductivity, water penetration test, and sorptivity. Further the microstructure analysis was done through SEM (scanning electron microscope), XRD (X-ray diffraction) and thermos-gravimetric analysis. The results demonstrated that CCB can be satisfactorily used as a replacement to conventional coarse aggregate to produce structural lightweight concrete and grinded CCB as a replacement to cement due to its pozzolanic characteristics. Muttaqin Hasan et al.[6] developed a lightweight concrete with aggregates obtained from diatomaceous earth. These lightweight aggregates were produced by two methods, in the first method the diatomaceous earth chunks were burned at 650 °C and crushed in a stone crusher to form aggregates and in the second method the pellets formed of diatomaceous earth were burned at 650°C. The authors summarized that the lightweight concrete obtained by adopting the first method had a low density and strength value, which be employed for non-structural elements and insulating works. While the lightweight concrete produced by adopting second method was classified as structural lightweight concrete. It was also found that with the inclusion of 5% sawdust to the lightweight diatomaceous earth aggregate, the mechanical performance of the lightweight concrete improved and the density of the concrete decreased. Suseno et al.[7] investigated the correlation between the destructive and non-destructive parameters of pumice based and scoria based lightweight concrete using simple linear regression analysis and multiple regression analysis. The analysis revealed that the expression for destructive characteristics of the lightweight concrete in the form of power equation consisting of rebound number and the pulse velocity showed better predicting accuracy compared to the linear, quadratic and exponential form of equations. In case of SonReb method of multiple regression analysis the statistical coefficient value was greater for the power form of equation compared to the individual regression analysis. Wei et al.[8] carried out an investigation on the effect of carbon and polypropylene fibre on lightweight concrete developed using expanded shale aggregate. The carbon and polypropylene fibre were added to the lightweight concrete individually and in hybrid form. Adding fibres to the lightweight concrete improved the segregation resistance and reduced the slump value. The flexural strength and split tensile strength were observed to increase with increase in the fibre quantity; the effect was more noticeable when hybrid fibres were incorporated. The ductility index and toughness ratio of hybrid fibre reinforced lightweight concrete was increased by about 32% and 30%, respectively. During the initial stages of loading the fibres had no effect on stress-strain pattern, however when incorporated in hybrid form, they had a superior effect on the post-peak behavior of the lightweight concrete.

Saradar et al.[9] found that inclusion of basalt fibres to the expanded clay aggregate based lightweight concrete reduced the slump and compressive strength. However, the addition of fibres improved the tensile strength and flexural performance of the lightweight concrete. It was also noted that the addition of silica fume and fly ash improved the compressive strength of the lightweight concrete when compared to non-pozzolanic lightweight concrete. Further, numerical analysis of the experimental results was carried out through ANFIS (adaptive neuro-fuzzy inference system). The ANFIS model was found to be highly accurate in predicting the strength of the lightweight concrete. Imran et al.[10] developed an environmental-friendly concrete by substituting the traditional coarse aggregate by RAC (recycled aggregate concrete) in volume proportions of 0%, 25%, 50%, 75%, 100% and cement by GGBFS (ground granulated blast-furnace slag) in volume proportions of 0%, 20%, 40%, 60%, 80%. The performance of the developed concrete was predicted using a white-box machine learning model called multivariate polynomial regression. The proposed model was found to be more robust than the linear regression model and support vector machine model. Basaran et al.[11] compiled a dataset consisting of concrete mixture with marble wastes in various forms such as coarse aggregate, fine aggregate or powder form. A multivariate regression analysis was conducted on the concrete mixture with marble wastes to develop equations for the prediction of change in concrete compressive strength with varying quantity and varying form of marble waste. The study indicated significant changes in compressive strength on replacing up to 50% of the normal aggregate by the waste marble aggregate. Zhang et al.[12] performed regression analysis on the high-strength lightweight concrete to predict its compressive strength. The key factors influencing the compressive strength of high-strength lightweight concrete are compressive strength of cylinder specimen, cement content, water to binder ratio, particle size of coarse aggregate, and fine aggregate ratio, which were determined through cluster analysis. The proposed regression model had R^2 value greater than 0.9 and RMSE (root mean square error) value below 1.05, indicating more accurate prediction.

The goal of this research work had been to conduct an experimental investigation on the performance of cinder based lightweight concrete. Based on experimental results, the viability of cinder aggregate in making lightweight concrete and the optimum dosage of polypropylene fibres are inferred. A Machine learning technique has been utilized to predict the performance parameters of lightweight concrete with fibre reinforcement.

2 Methodology

2.1 Test Material

Ordinary Portland cement, grade 53, with a specific gravity of 3.15 has been used. Fine aggregate consists of a mixture of M-sand and natural river sand conforming to IS 383:1970 Zone III, with a combined specific gravity of 2.67. Two types of coarse aggregates, both conforming to IS 2386:1963 were used: waste cinder aggregate of size 12 mm to 20 mm and specific gravity 2.1, and crushed granite of maximum particle size 20 mm and specific gravity 2.72. Potable water was used in the mixing and curing of the concrete. Micro-reinforcement consisted of polypropylene fibres of 12 mm length with a specific gravity of 0.91. ConplastSP430, a water reducing admixture, was used as superplasticizer for achieving workability. The mix design was prepared using IS 10262: 2019. The mix ratio of 1:1.96:3.56 was adopted with a water-cement ratio of 0.5 and cement content of 350kg/m^3.

2.2 Test Program

The lightweight concrete specimens were prepared by substituting 40% of the conventional coarse aggregate by cinder aggregate. Polypropylene fibre was added to this cinder based lightweight concrete in volume proportions of 0.1%, 0.2%, 0.3%, and 0.4%. The ideal quantity of polypropylene fibre in cinder aggregate based lightweight concrete was determined through the experimental results.

2.3 Test Method

Concrete cube specimens 150 mm × 150 mm × 150 mm and cylinder specimens 150 mm × 300 mm were cast for determining the compressive strength. The cube specimen and cylinder specimen were subjected to compression loading in a standard compression testing machine. The cube compressive strength test was performed as per IS 516:2018 while the cylinder compressive strength test was performed as per ASTM C39. Concrete prism specimens 100 mm × 100 mm × 500 mm were cast for determining the flexural strength. The prism specimen was subjected to two-point loading in a standard loading frame. Cylindrical specimens 150 mm × 300 mm were cast for determining the modulus of elasticity. The cylinder specimen was fitted with compressometer before being tested in a standard compression testing machine. The flexural strength test and modulus of elasticity test were performed as per IS 516:2018. The results were calculated by taking the average value of three concrete specimens.

3 Results and Discussion

3.1 Compressive Strength

The compressive strength test was conducted on cube and cylinder specimens of cinder based aggregate lightweight concrete with varying micro-reinforcement content. The effect of polypropylene fibre on the compressive strength of the concrete are shown in Figures 1 and 2. It was noted that for 0.3% of polypropylene fibre quantity the cube compressive strength and cylinder compressive strength increased by 30% and 32% respectively. As the polypropylene fibre dosage was increased above this level, the compressive strength decreased. The increase in compressive strength was due to the inclusion of polypropylene fibres in lightweight concrete. The polypropylene fibre controls the propagation of short discrete cracks that were developed during the initial loading period, thereby enhancing the structural integrity of the concrete and the load bearing capacity.

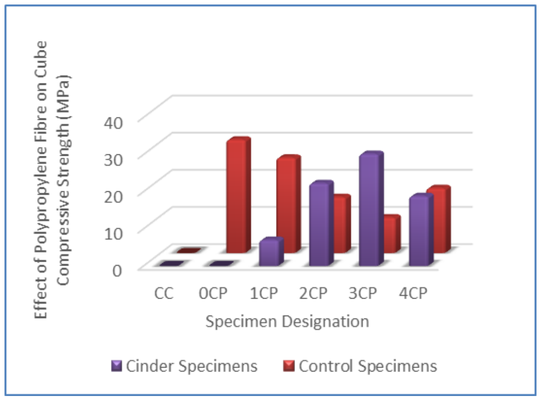

Fig 1. Effect of Polypropylene Fibre on Cube compressive strength

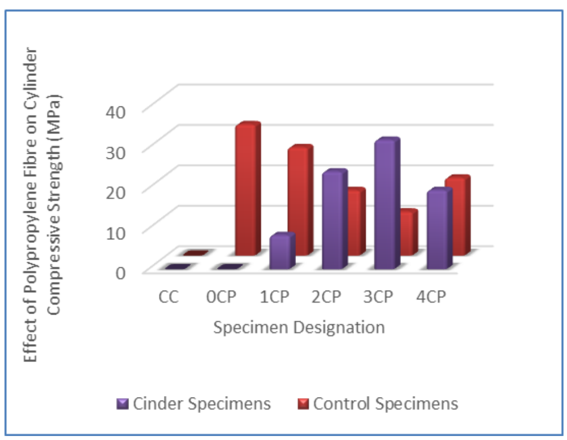

Fig 2. Effect of Polypropylene Fibre on Cylinder compressive strength

3.2 Modulus of Rupture

The flexural strength test was performed on polypropylene fibre reinforced cinder based lightweight concrete prism specimens. The effect of polypropylene fibre on the flexural strength of the concrete are shown in Figure 3. The flexural strength of the cinder based lightweight concrete increased from 5.4 MPa to 6.8 MPa as the polypropylene fibre dosage was increased from 0% to 0.4%. The flexural strength of the lightweight concrete was found to increase with increase in the polypropylene fibre content. The fibres provided a strong cohesive link between the aggregates and cement mortar which caused a rise in the flexural strength of the concrete.

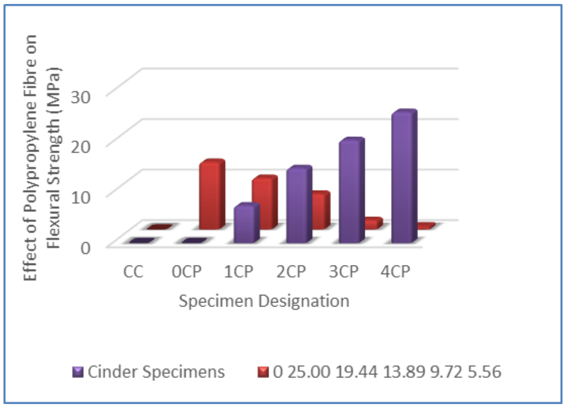

Fig 3. Effect of Polypropylene Fibre on Flexural strength

3.3 Modulus of Elasticity

The modulus of elasticity of cinder based lightweight concrete with polypropylene fibre was determined by testing cylindrical specimens and the effect of polypropylene fibre on the modulus of elasticity of concrete are shown in Figure 4. The modulus of elasticity value of the lightweight concrete was found to increase as the polypropylene fibre content increased. At 0.4% volume proportion of polypropylene fibre, the modulus of elasticity value of the concrete was increased to 14.67% compared to the lightweight concrete without fibre. The rise in the modulus of elasticity value of the lightweight concrete with fibre reinforcement was due to the higher modulus of elasticity value of the polypropylene fibre.

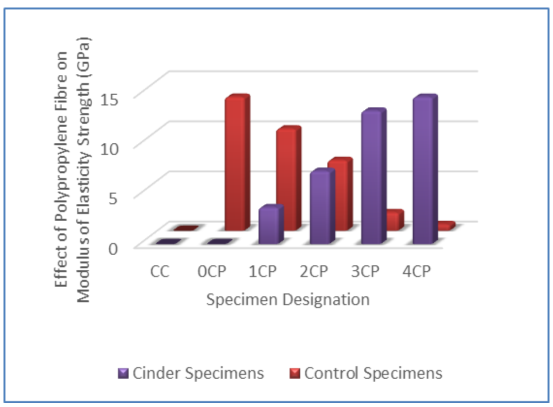

Fig 4. Effect of Polypropylene Fibre on Modulus of elasticity

3.4 Regression Analysis

3.4.1 Data Collection

For analysis purpose, a database on fibre reinforced lightweight aggregate concrete has been created referring to several literature[(13–27)]. The constituents of the lightweight concrete such as mineral admixture, cement content, fine aggregate, coarse aggregate, lightweight aggregate, water and fibre content were taken as response variables and the performance parameters which included compressive strength, flexural strength and modulus of elasticity were taken as the predictor variables.

3.4.2 Multiple Linear Regression (LR)

Regression analysis is a more commonly used statistical methodology that provides techniques to establish the correlation between response (dependent) and predictor (independent) variable. The simplest form of multiple linear regression based on which the regression model is developed is given by Equation (1).

$$Y = b + a_1X_1 + a_2X_2 + \ldots a_nX_n \quad (1)$$

Where Y represents the predictor variable, X_1, X_2, … X_n represents the response variable, b is the Y-intercept when X_1, X_2, … X_n are zero, and a_1, a_2, … a_n are the regression coefficient.

Python, a structured high-level programming language was chosen to carry out the multiple linear regression analysis. The dataset was imported in CSV file format and put into two categories namely train data and test data. The multiple linear regression was carried out on the train dataset and the best fit regression model was used to predict the results for the test dataset. The accuracy of the regression model developed was determined by comparing the experimental outcome and the predicted outcome.

3.4.3 Results

Multiple linear regression was conducted to predict the correlation between predictor variables and response variables. The reliability of predicted results of regression model were ascertained through statistical indicators which includes R^2 (coefficient of regression), RMSE (root mean squared error) and MAPE (mean absolute percentage error). The regression model and the statistical error coefficients for the compressive strength, flexural strength, and modulus of elasticity of the fibre reinforced lightweight concrete are consolidated in Table 1.

Table 1. Regression Equations with Statistical Indicators

Parameter	Regression Equation	R^2	RMSE	MAPE
Compressive Strength	Fck(F) = 34.964 + 0.015*MA + 0.041*CM - 0.021*FA + 0.001*CA - 0.007*LA + 0.007*WA + 1.492*FB	0.9721	6.6248	15.7047
Flexural Strength	Fr(F) = 14.8645 - 0.0019*MA - 0.0031*CM - 0.0031*FA - 0.002*CA - 0.0034*LA- 0.02*WA + 0.8449*FB	0.9678	1.0222	15.1995
Modulus of Elasticity	MoE(F) = -14.703 - 0.0127*MA + 0.0157*CM + 0.0195*FA + 0.0246*CA + 0.018*LA - 0.0017*WA + 1.8464*FB	0.9664	4.6982	14.7628

The terms used in the regression equation presented are MA-mineral admixture (kg/m^3), CM-cement content (kg/m^3), FA-fine aggregate (kg/m^3), CA-coarse aggregate (kg/m^3), LA-lightweight aggregate (kg/m^3), WA-water (kg/m^3) and FB-fibre content (%) and Fck(F)-compressive strength (MPa), Fr(F)-flexural strength (MPa) and MoE(F)-modulus of elasticity (GPa).

The R^2, RMSE and MAPE values for predicting the compressive strength, flexural strength and modulus of elasticity of the fibre reinforced lightweight concrete were observed to be 0.9721, 6.6248 and 15.7047; 0.9678, 1.0222 and 15.1995; 0.9664, 4.6982 and 14.7628 respectively. The regression models had R^2 value greater than 90% and lower RMSE and MAPE indicating a precise strength prediction for fibre reinforced lightweight concrete. For validation purpose, scatter plots were drawn between the predicted results and the experimental results of current study and previous literature which are shown through Figures 5, 6 and 7. The statistical error coefficients and scatter plots demonstrated that performance of the fibre reinforced lightweight concrete were closely predicted by the developed regression equations.

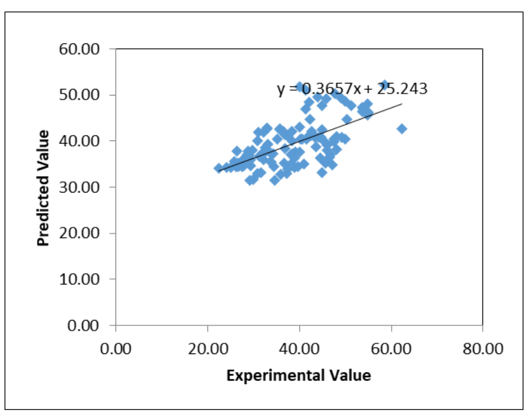

Fig 5. Scatter Plot for Compressive Strength

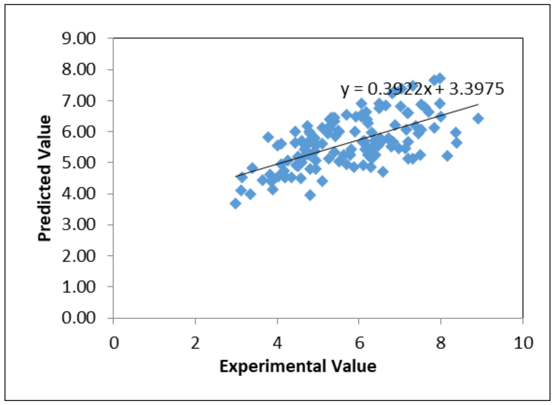

Fig 6. Scatter Plot for Flexural Strength

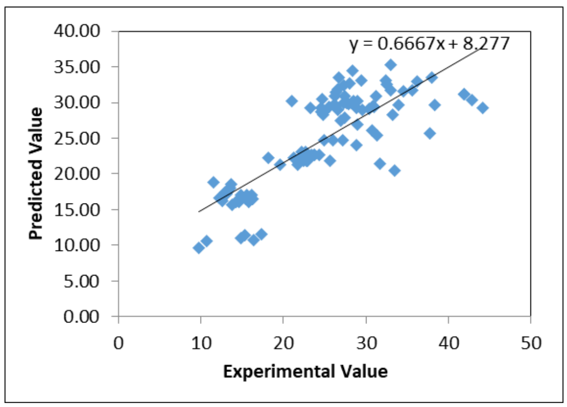

Fig 7. Scatter Plot for Modulus of Elasticity

4 Conclusions

In accordance to the compressive strength test results, 0.3% polypropylene fibre was optimum content for the cinder based lightweight concrete. The compressive strength of lightweight concrete was increased to 30% in cube specimens and 32% in cylinder specimens when 0.3% polypropylene fibre was added. The addition of 0.4% polypropylene fibre increases the flexural strength of the lightweight concrete from 5.4 MPa to 6.8 MPa. The lightweight concrete was observed to have a higher modulus of elasticity as the quantity of polypropylene fibre increased.

The scatter plots and the statistical indicators with R^2 value of 0.9721, 0.9678 and 0.9664 for compressive strength, flexural strength and modulus of elasticity respectively, demonstrated that the proposed multiple linear regression model can predict the performance parameters of lightweight concrete with micro-reinforcement fairly well.

This study facilitates the future research on durability behaviour of lightweight concrete with fibre reinforcement and conduction of non-destructive tests on the fibre reinforced concrete. Further, the experimental test data can be utilized to conduct numerical analysis using neural networks.

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