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Properties of eco-friendly concrete with partial replacement of fine aggregate with recycled plastic waste and cement by silica fume

[1]Chinsu Mereena Joy, [2]Ramaswamy K P, [3]Abhijith S, [3]Abhilash G, [3]Mohamed Sabir Najeem,

[3]Sanjay Krishnan R

[1]Associate Professor, [2]Professor, [3]Undergraduate Student
Department of Civil Engineering,
TKM College of Engineering, Kollam, Kerala, India

Abstract : Solid waste could negatively affect the environment. Problems stem from factors such as the difficulty of waste recycling and limited reuse. Plastic is an important type of solid waste with a strong negative environmental impact. To improve sustainability and reduce usage of natural resources, innovative solutions are required. Incorporating crushed plastic waste as replacement for aggregate is one such innovative solution that can be adopted. This study aims to investigate the effects of utilizing recycled plastic waste as a partial substitute for fine aggregate in concrete. The effects of recycled plastic on the mechanical properties of concrete were studied. Both the fresh (workability) and hardened properties (unit weight, compressive strength, splitting tensile strength, pulse velocity and impact strength) of concrete were investigated. For this, substitution levels of 10%, 20%, and 30% were adopted for the experimental studies. Additionally, silica fume was also used for partial replacement of cement. A machine learning model to predict the compressive strength of concrete containing recycled plastic aggregate was also developed.

***Index Terms* – Plastic waste, silica fume, mechanical properties, prediction model, partial replacement**

I. INTRODUCTION

Plastic waste is becoming more and more prevalent, making up a significant portion of solid waste. Because this plastic waste is not a biodegradable material it creates a considerable threat to the environment. But recycling this kind of waste and utilizing this material in concrete, seems to be the greatest option because it has both ecological and economic benefits. Due to the rising cost of construction materials, researchers have investigated and determined the use of locally accessible materials to lower the cost of its components and, consequently, the overall construction cost. Therefore, a new approach to sustainable development is required so that such an approach should be able to optimize the elimination, reuse, and recycling of such solid waste. To diminish the environmental consequences on the construction sector, studies to use of such waste have been conducted. The recycling of solid waste as a partial substitute for aggregate in the construction industry results in decreased demand for natural raw material production along with a reduction in waste disposal capacity.

The use of recycled plastic waste in concrete can reduce the dead weight of concrete, thus lowering the earthquake risk of a building. However, incorporating recycled plastic waste in concrete has several negative effects such as poor workability and deterioration of mechanical behaviour. Guendouz et al. (2016) showed that the use of plastic waste as a partial replacement of sand contributes to reducing the bulk density, decreasing the air content, and causing an increase in compressive and flexural strength for 10% and 20% of replacement. But a higher percentage of replacement shows a reduction in strength. Almeshal et al. (2020) demonstrated that a decrease in unit weight, and the replacement of sand damaged the hardened properties of the concrete, and demonstrated that a specific percentage of plastic waste can be disposed of and can be used successfully in the construction industry. The effects of the size and shape of recycled polyethylene terephthalate aggregate on the fresh and hardened properties and also the abrasion resistance was evaluated by Saikia and Brito (2014). The workability, compressive, tensile splitting, and flexural strength decrease with the increase in plastic content but the abrasion resistance increases with the plastic content due to the crack-arresting effect. Adding silica fume to concrete at varying replacement levels (5%, 10%, 15%, and 20%) resulted in improved compressive strength after 28 days. The use of silica fumes positively affected the strength properties of concrete and was attributed to the refinement of the pore size distribution, resulting in higher capillary tension and more contraction of the cement paste (Siddique, 2011). Several researchers have investigated the utilisation of plastic waste in concrete. The present study investigates the effect of Silica Fume as a partial replacement of cement in concrete containing recycled plastic aggregates. Artificial intelligence techniques, specifically the creation, training, and use of specialized algorithms to ascertain the properties of the resultant concrete, can be used to enhance the production of concrete (Beskopylny et al. 2022). This study also aims to develop a machine-learning model to predict the compressive strength of concrete containing recycled plastic aggregate.

II. MATERIALS USED

In this study, Ordinary Portland Cement of 53 grade (IS 12269-1987) was used. Manufactured sand which conforms to IS 383 with specific gravity 2.65 and fineness modulus 2.90, Crushed stone of maximum size 20mm and specific gravity 2.65, and plastic aggregates with specific gravity 0.92 were used as aggregates. The plastic aggregates used in this project are recycled HDPE (High Density Polyethylene) plastics. High-reactive microsilica was used for the study as partial replacement of cement. The particle size distribution of the aggregates is shown in Fig. 2.1

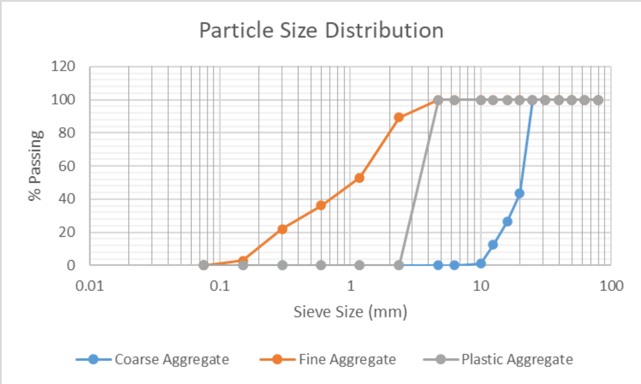

Fig 2.1 Particle size distribution of the aggregates

III. Mix Design

The mix design was done according to IS 10262-2019 with 320 kg/m^3 of cement, 728 kg/m^3 of fine aggregate, 1192 kg/m^3 of coarse aggregate, water cement ratio of 0.50, and 1% of superplasticizer (CONPLAST SP430) by weight of cement. The control mix consists of OPC 53 grade cement, fine aggregate, coarse aggregate, and 10% silica fume for partial replacement for cement. Three replacement ratios were adopted to determine the effect of recycled plastic aggregates on the properties of concrete. The replacement ratios used in the study were 10%, 20%, and 30% by weight of fine aggregate. The nomenclature of various mixes is control mix, 10% plastic, 20% plastic, and 30% plastic respectively.

IV. EXPERIMENTAL TEST PROCEDURES

Various standard experimental tests were conducted with different quantities of recycled aggregates to determine the fresh and hardened properties. The workability of concrete was measured in terms of slump as per IS 1199. The hardened properties were determined by conducting compression test, ultrasonic pulse velocity (UPV) test, Dynamic modulus of elasticity of concrete using UPV Measurements, Split Tensile Test, and impact test (Fig.4.1). The compression test (as per IS 516 code) was conducted in a compression testing machine cube using specimens of 100mm x 100mm x 100mm size. The cubes were cast from fresh concrete, and are left to cure for 3, 7, 28 days under standard conditions. The cubes are then placed on a compression testing machine with a load capacity of at least 2000 kN. A compressive load is applied to the cube at a constant rate until the cube fails. During the test, the load of the cubes is recorded continuously, and the maximum load applied just before failure is noted. The compressive strength values for different proportions of recycled aggregates were tested for the 7, 14, and 28 days. An ultrasonic pulse velocity test is an in-situ, non-destructive test to check the quality of concrete. In this test, the strength and quality of concrete is assessed by measuring the velocity of an ultrasonic pulse passing through a concrete. Higher velocities indicate good quality and continuity of the material, while slower velocities may indicate concrete with many cracks or voids. The dynamic modulus of elasticity refers to the material's ability to resist deformation under dynamic or oscillatory loading conditions, such as vibrations or seismic forces. The dynamic modulus of elasticity (E) of the concrete may be determined from the pulse velocity and dynamic Poisson's ratio (μ). The value of the dynamic poisson's ratio varies from 0.20 to 0.35, with 0.24 as average considered for the analysis. The split tensile strength of concrete is a measure of its ability to resist tensile stress and formation of cracks. It is an important parameter to consider in the design and construction of various concrete structures. The split tensile strength test (as per IS 5816 code) of concrete involves preparing a cylindrical specimen of concrete, typically with a diameter of 150mm and height of 300mm. The impact strength test of concrete (as per ACI: 544 - 2R – 89) was conducted by subjecting a disc-shaped specimen to a single impact load. The test was carried out using an impact testing machine which consists of a pendulum that is released from a known height to strike the specimen. The height of the pendulum and the resulting impact force were measured and the energy absorbed by the specimen was calculated. The disc specimen used in this test was 150mm in diameter and 50mm in height.

Fig.4.1 a) slump cone test, b) compression testing machine, c) UPV testing apparatus, d) Impact strength testing equipment

V. RESULTS AND DISCUSSION

5.1 Properties of fresh concrete

5.1.1 Slump

Good workability (60 mm) was obtained for 0 % replacement with plastic and while increasing the content of plastic, workability decreases. When it comes to 30% replacement, workability is reduced to zero. Fig 5.1 shows the variation of workability to increase in percentage replacement. The reduction in workability is due to an increase in water demand, increased surface area, reduced air entrainment, and increased viscosity.

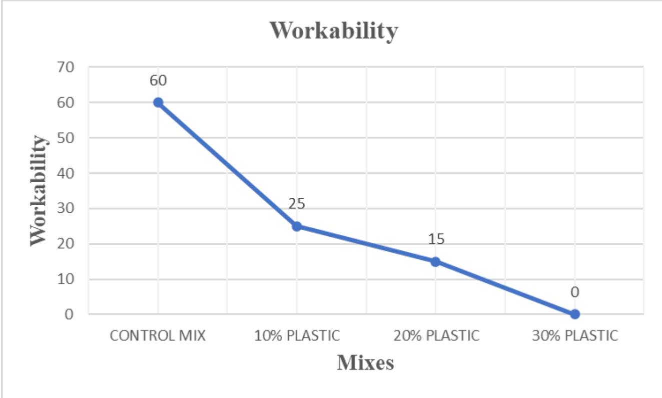

Fig 5.1 Workability of various mixes

5.2 Properties of hardened concrete

5.2.1 Density of Concrete

The density of the mixes decreases as the replacement of plastic with sand increases. The non-plastic incorporated specimen will have maximum density and specimens with 30% replacement will have lower density. This is due to the fact that adding plastic, which has lower density than water to the mix proportion as a weight replacement of sand, gives a higher volume of light weight concrete. i.e., the plastic takes up space in the mixture without contributing as much mass. As more plastic is added to the mixture, the overall density of the specimen will decrease because there is less mass per unit volume. This can have an impact on the mechanical properties of the material, such as its strength, stiffness, and durability. In Fig 5.2 the decreasing trend of density with respect to percentage increase in replacement of plastic can be seen.

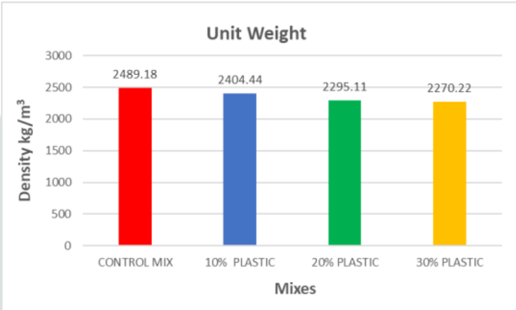

Fig 5.2 Density of mixes

5.2.2 Compressive Strength

The effect of recycled plastic aggregates on the compressive strength on concrete is shown in Fig 5.3. The control mix attains a 28th day strength which is 53.5% greater than $3rd$ day strength and 22.7% greater than 7^{th} day strength. The 10% plastic mix attains a 28^{th} day strength which is 65.3% greater than $3rd$ day strength and 25% greater than 7th day strength. The 20% plastic mix attains a 28^{th} day strength which is 44.8% greater than $3rd$ day strength and 25.8% greater than 7th day strength. The 30% plastic mix attains a 28th day strength which is 28.7% greater than $3rd$ day strength and 20.2% greater than 7th day strength. Fig 4.2 shows the variation of compressive strength for different mixes at $3rd$ day, 7th day and 28th day. The compressive strength of 10% plastic incorporated mix is having a similar strength pattern of 0% plastic (control mix) incorporated specimen. The difference in $3rd$ day, 7th day and 28th day strength value obtained for these mixes is comparatively negligible. But the 20% and 30% plastic incorporated specimens obtained a strength that shows more variation from the control mix. 30% plastic replaced specimens have low compressive strength value.

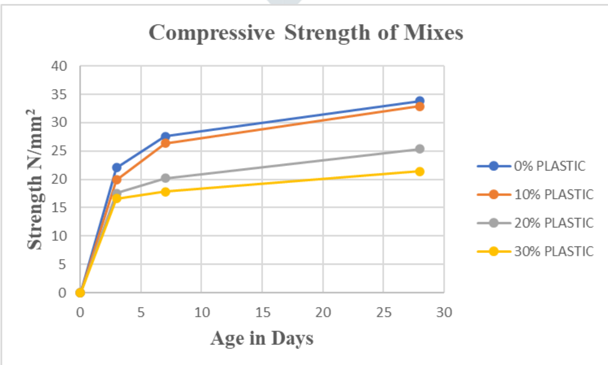

Fig 5.3 Variation of compressive strength of mixes

5.2.3 UPV test

The quality of concrete is determined by UPV values. The variation of UPV values for different mixes at $3rd$ day, 7th day and 28^{th} day are depicted in Fig 5.4. The velocity obtained by 0% plastic mix is higher. As the percentage increases the quality of concrete decreases. The quality of concrete obtained at 28th day is of good to excellent grade. Compressive strength similar to the control mix is obtained for mix with 10% plastic replacement, further increase of replacement decreases the strength. Strength for 30% plastic replacement has the lower value.

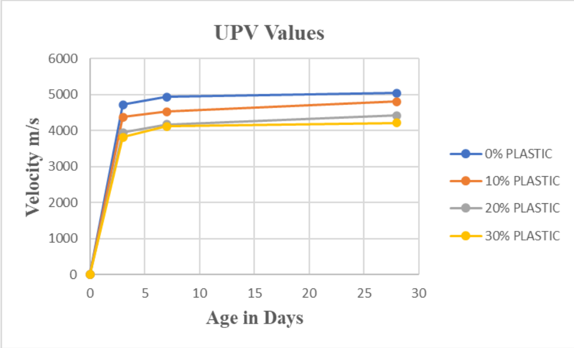

Fig 5.4 UPV values of various mixes

5.2.4 Dynamic Modulus Elasticity of Concrete

Using UPV test, the dynamic modulus of elasticity of concrete can be calculated. The dynamic modulus of elasticity of the mixes is shown in Fig 5.5. The control mix has higher dynamic modulus of elasticity and 30% plastic incorporated specimens have a lower value for dynamic modulus. The 10% plastic incorporated plastic has a value near to the value of the control mix and the 20% and 30% plastic substituted specimens have much lower values. As the percentage of replacement increases the value of dynamic modulus decreases. The 10% plastic specimens have a 12.45% lower value. For 20% and 30% plastic specimens, the value decreases by 29.16% and 36.43% respectively.

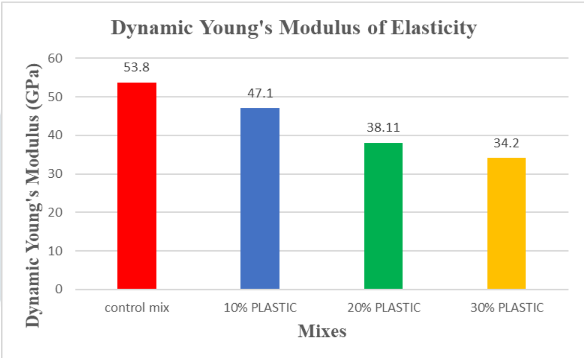

Fig.5.5 Dynamic modulus of various mixes

5.2.5 Split Tensile Strength

The variation of split tensile strength for different mixes with age in days is shown in Fig.5.6. The split tensile strength of 10% plastic incorporated mix is having a similar strength pattern of 0% plastic incorporated specimen. The difference in $3rd$ day, 7th day and 28th day split strength value obtained for these mixes is comparatively small. The 20% and 30% plastic incorporated specimens obtained a strength which is having a low strength compared to strength of 0% plastic incorporated specimen. 30% plastic replaced specimens have low compressive strength value. The control mix attains a 28th day strength which is 12.5% greater than 3day strength and 4.16% greater than 7thday strength. The 10% plastic incorporated mix attains a 28thday strength which is 13.6% greater than $3rd$ day strength and 9.1% greater than 7thday strength.

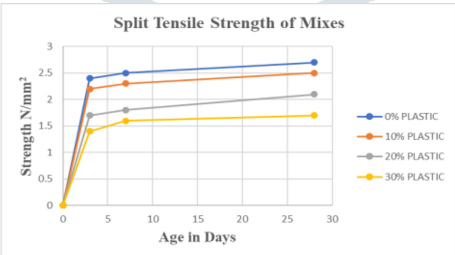

Fig.5.6 Variation of split tensile strength of different mixes

5.2.6 Impact Strength Test

The impact strength of different mixes at crack and at failure is shown in Fig.5.7. The impact strength increases with an increase in the amount of plastic content, where 30% plastic incorporated specimen has the highest impact energy absorption. Impact energy obtained at failure is that much energy the specimen could absorb before the failure of specimen occurred.

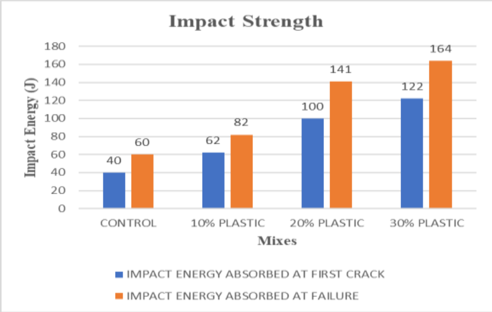

Fig.5.7 Impact strength of various mixes at first crack and at failure.

VI PREDICTION OF COMPRESSIVE STRENGTH USING MACHINE LEARNING

Machine learning has the potential to automate the prediction of concrete strength and improve its accuracy. In this study machine learning techniques were used to predict the compressive strength of concrete based on its ingredients. Four different models, including Linear Regression, and Random Forest Regression, were trained and evaluated using evaluation metrics such as MSE, and RMSE.

The dataset used in this study was the "Concrete Compressive Strength" dataset, based on experimentatal results. The dataset contains concrete ingredients, including cement, silica fume, water, superplasticizer, coarse aggregate, plastic aggregate and fine aggregate. The compressive strength of concrete, measured in MPa, is the target variable. The dataset was pre-processed by removing duplicates and scaling the features.

The methodology consists of the following steps:

- Importing Libraries: The necessary libraries, including pandas, NumPy, and scikit-learn, were imported.
- Importing Dataset: The "Concrete Compressive Strength" dataset was imported into a pandas data frame.
- Splitting Data into Training and Testing Sets: The dataset was split into training and testing sets using a 70:30 ratio.
- Initializing Models: Four different models, including Linear Regression, Ridge regression, Lasso regression and Random Forest Regression, were initialized.
- Training Models: Each model was trained on the training dataset.
- Evaluating Models: Each model was evaluated on the testing dataset using evaluation metrics such as MSE, and RMSE.

Table 6.1 shows the evaluation metrics for each model. The Random Forest Regression model outperformed the other models, with the lowest MSE and RMSE.

Table 6.1 Evaluation Metrics for Different Machine Learning Model

Model	MSE	RMSE
Linear Regression	20.17	4.49
Ridge Regression	19.25	4.38
Lasso Regression	18.25	4.49
Random Forest Regression	14.93	3.86

The Random Forest Regression model was found to outperform the other models, achieving an MSE of 14.93 and an RMSE of 3.86. This indicates that the Random Forest model was able to capture the non-linear relationships between the input features and the target variable more effectively than the other models. The model can be used in the construction industry to predict the compressive strength of concrete with recycled plastic as partial replacement for sand, which is a critical parameter in ensuring the safety and durability of the structures built with it. Accurate predictions can help engineers and builders optimize the mix design and curing process, leading to better quality concrete and reducing costs associated with overdesign.

VII CONCLUSION

The project aims to determine the properties of concrete with partial replacement of fine aggregate with recycled plastic waste at various percentages, and cement with 10% silica fume. A prediction model to predict the compressive strength of concrete with recycled plastic as a partial replacement for sand was developed. The following conclusions were drawn based on the study:

- The workability of concrete containing recycled plastic aggregates was reduced.
- As the replacement ratio of plastic in concrete is increased, the compressive strength decreases. For the 10%, 20%,30% plastic concrete mixes, the compressive strength decreased by 2%,24%,36% respectively compared to the control mix.
- As the replacement ratio of plastic in concrete is increased, the split tensile strength decreases. For the 10%, 20%, 30% plastic concrete mixes, the split tensile strength decreased by 7%, 22%, 37% compared to the control mix.
- UPV which reflects the quality of the concrete decreased with an increase in the proportion of plastic. Its value decreased by 5%,12%,16% for 10%, 20%,30% plastic replaced specimen compared to the control mix.
- The impact strength has significantly increased with an increase in plastic content. Impact energy increases with a percentage increase of 36%, 135%, and 173% than the control mix for replacement of plastic aggregates of 10%, 20%, and 30% respectively.
- A prediction model to predict the compressive strength of concrete with recycled plastic as a partial replacement for sand and cement partially replaced with 10% silica fume was developed. The Random Forest model outperformed other models and can be used in the construction industry to optimize mix design and reduce costs associated with overdesign.

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