Machine Learning Prediction and Experimental Validation of Frost Resistance of Concrete Reinforced With Steel, Basalt and Polypropylene Fibers

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Abstract: Cold climates usually expose concrete structures to frequent freeze-thaw effects, the effects are likely to create microcracks, surface scaling, and gradual material erosion of the concrete matrix, which eventually compromises compressive and tensile strength. In order to increase the durability and structural performance in such a harsh environment, fiber reinforcement has been extensively used. This paper is an exploration of the freeze-thaw resistance of concrete reinforced using three types of fibers, namely steel, basalt, and polypropylene. Cubic samples (100 x 100 x 100 mm) were made with different types of fibers, contents, and lengths in a controlled manner of freeze-thaw cycles, following standard procedures. A Random Forest Regression (RFR) model was created so that it could be used to predict the number of freeze-thaw cycles each specimen could withstand depending on the type of fiber content as well as length. The model was highly predictive with a cross-validation R^2=0.9648. The analysis of feature importance showed that the most significant factors influencing the durability were fiber type and content, and the fiber length had a moderating impact. The optimum combinations of fibers were determined using the predictive model whereby steel fibers with 2.0% content and 30 mm length demonstrated the highest predicted freeze-thaw resistance of 210 cycles. This combination of experimental and data-driven research represents the opportunity of using machine learning and laboratory testing to refine fiber-reinforced concrete to withstand temperatures in extreme cold conditions. The findings present a realistic guideline to engineers in choosing types of fibers, contents, and lengths of fibers so as to maximize the durability, minimize the cost of maintenance, and increase the service life of the structures in freeze-thaw conditions that are covered with concrete.

1 INTRODUCTION

This is due to the fact that cold environments expose concrete structures to extreme conditions, which are mainly through the freezing and thawing processes [1]. Once the water in the pores of concrete is frozen and thaws, it results in internal stress, which leads to microcracking, surface scaling, and gradual weakening of the concrete matrix [2].

The processes lower compressive strength, enhance permeability, and reduce service life, which present extreme problems to infrastructures, including bridges, pavements, and buildings, in low-temperature regions [3]. Fixing the freeze-thaw-damaged structures is expensive, which underlines the necessity to create concrete with a better life cycle [4].

Efficient reinforcement systems and structural design modifications have become essential methods to improve the durability and mechanical performance of critical infrastructure elements under severe environmental regimes [5]. The fibers distributed through the concrete matrix are crack arrestors that bridge the microcracks, retard the crack propagation, and enhance post-cracking behavior. The most popular ones are steel, basalt, and polypropylene fibers, and they all have varying advantages [6].

Being made of volcanic rock, basalt fibers can be used when corrosion resistance is needed as well as chemical stability and high tensile strength, thus suitable to be used in harsh conditions. Polypropylene fibers are light, chemically inactive, and regulate microcracking and plastic contraction without greatly raising the density of concrete [7], [8].

The past research has revealed that freeze-thaw durability is enhanced by fiber addition. Li et al. (2020) have indicated that the mass loss of reactive powder concrete decreased with the addition of basalt fiber content and that strengthening the compressive strength remained upon repeated freeze-thaw cycles [9]. Yuan et al. (2023) noted that steel or basalt fibers in recycled concrete stabilized the compressive strength of the materials in freeze-thaw conditions [10]. Consistent with this, Wang et al. have shown that polypropylene fibers enhanced residual compressive strength in lightweight aggregate-based concrete that was taken through freeze-thaw cycles [11], [12].

Although these works prove the efficiency of fibers, most of them are based on the performance of single-fiber systems, and little is done to compare the performance of various types of fibers under the same conditions of the tests [13], [14].

Over the previous years, there has been an increase in the utilization of information-based methods in the civil engineering industry, which offered new prospects to speed up the process of material optimization [15]-[17]. The complexity of non-linear correlations between mixture parameters and performance indicators can be accounted for by machine learning (ML) techniques, which allow predicting reliably without the necessity of carrying out trial after trial of each combination of parameters [18], [19]. Recent comprehensive reviews have further underscored the validity of utilizing advanced machine learning architectures to systematically evaluate and map freeze-thaw degradation in concrete matrices [20]. Regarding the durability aspect, predictive models may be used to assist in making decisions by determining the most effective parameters and offering the best material arrangements [21]-[23]. These strategies are consistent with the current trends in intelligent infrastructure design, performance evaluation with a durability-based framework, and computational material engineering [24].

Thus, this paper is a combined experimental and machine learning research on freeze-thaw resistance in concrete strengthened by steel, basalt, and polypropylene fibers [25], [26]. The objectives of the work are to experimentally test the freeze-thaw stability of concrete when using various types and dosages of fibers, test the relative performance of the various fibers under similar testing conditions, and create a predictive model using Random Forest Regression to predict freeze-thaw resistance using fiber parameters [27], [28]. The suggested solution offers realistic advice on the fiber type, content, and length selection in order to maximize durability, minimize maintenance operation, and increase the lifespan of exposed concrete builds in a freeze-thaw environment [29], [30].

This study, in contrast to most earlier studies that analyze a single type of fiber, offers a comparative framework and two-way integration of laboratory tests and a powerful machine learning model to facilitate the design of materials based on durability [31].

2 MATERIALS AND METHODS

2.1 Materials

The experimental work was conducted on Portland cement, fine and coarse aggregates, water, and three kinds of fibers - basalt, polypropylene, and steel in order to determine their influences on freeze-thaw durability.

The research used basalt fibers produced by the Bazalt Uzbekistan enterprise located in the Jizzakh region. These fibers have a density of 2650 kg/m³, 3500 MPa tensile strength, 110 GPa elastic modulus, 17 µm diameter, and 10, 20, and 30 mm length.

Polypropylene fibers were used to regulate the microcrack formation and plastic shrinkage on the concrete matrix. The density of the polypropylene fibers is 910 kg/m³, with a tensile strength of 500 MPa, an elastic modulus of 35 GPa, a diameter of 18.5 µm, and lengths of 10, 20, and 30 mm.

The density of the steel fibers is 7850 kg/m³, tensile strength is 1100 MPa, elastic modulus is 200 GPa, diameter is 0.3 mm, and length is 30 mm. The material consumption for 1m³ of concrete mix in this test is shown in Table 1.

Table 1: Material for 1 m³ of concrete mix.

Material	Quantity
Cement (kg)	440
Fine aggregate (kg)	1025
Coarse aggregate (kg)	815
Water (kg)	180
Basalt, polypropylene fibers (%)	0.1; 0.2; 0.3
Steel fibers (%)	1.0; 2.0; 3.0

2.2 Experimental Program and Specimen Preparation

The testing studies were conducted in the experimental laboratory of Namangan State Technical University. This research was aimed at testing the freeze-thaw resistance of fiber reinforced concrete that included basalt, polypropylene, and steel fibers.

To identify frost resistance, cube specimens (100 x 100 x 100 mm) were made according to the demands of GOST 10060-2012 (Interstate Standard. Concretes. Methods for determining frost resistance). A total of 22 sets of cube specimens were made, comprising control specimens with no fibers and fiber-reinforced specimens with various types and contents of fibers.

The specimens were cast and kept in a controlled laboratory environment (24 hours), after which they were demolded. All specimens were labeled properly and then cured in a regular curing chamber under normal conditions over a period of 28 days with enough hydration and strength growth before freeze-thaw testing. The initial mass and geometric size of each cube specimen were weighed prior to immersion into water and exposure to freeze-thaw cycles. In control of the temperature during tests, a temperature sensor (thermometer) was installed in a specially chosen concrete specimen to provide proper control of the freezing and thawing conditions.

Before testing, all specimens were saturated with tap water. For water saturation of the control specimens, the cubes were initially immersed in water to 1/3 of their height and maintained in this condition for 24 h. Subsequently, the water level was increased to 2/3 of the specimen height, and the specimens were kept under these conditions for an additional 24 h. After that, the specimens were fully immersed in water for 48 h. The water level throughout the saturation process was maintained at 20 mm above the top of the specimens, which maintains full saturation and uniform saturation as seen in Figure 1.

Figure 1: The process of preserving cube samples in water.

The specimens were dried and weighed on a balance after being removed from the water and then stored under the condition of dry air at (20 ± 2)°C at a relative humidity of at least 55%. This was followed by the testing procedures. The samples were frozen in a freezer with the capacity of preserving the temperature of -18 ± 2°C and stored and kept in the freezer until the period demanded. The process of freezing the samples is shown in Figure 2.

Figure 2: Experience testing process.

In the preparation of the thawing process, an 800 × 1000 × 150 mm³ container was placed in the laboratory and was supplied with equipment to maintain the stability of the temperature. Thawing was done in water at (20 ± 2)°C and in a special rectangular-section container where the level of water was maintained 50 mm above the top face of cube specimens. The container was made in such a way that the cube specimens could be left overnight for several days under controlled conditions.

The cube specimens were then frozen at (-18± 2)°C and then thawed in water at (20 ± 2)°C over 1.5 h. The mass of cube specimens was measured during every freeze-thaw cycle to track changes that occurred as a result of cyclic freezing and thawing. Freeze-thaw resistance was given the number of cycles when the specimen mass loss attained 5 percent or more, which was set as the failure criterion in this experiment.

2.3 Digital Assessment

In order to supplement the experimental research, a digital evaluation strategy was adopted to assess how the type of fibers, content, and length of fibers affect the freeze-thaw stability of the concrete. A predictive model based on machine learning was utilized by taking the number of freeze-thaw cycles of cubic specimens (100x100x100 mm) as the target variable.

The input characteristics were fiber type (basalt, polypropylene, steel), fiber content percentage, and fiber length.

The regression model was created that predicts the quantity of freeze-thaw cycles that each concrete specimen would resist. Test data and 5-fold cross-validation were used to measure the model performance, the parameters being R^2, Mean Absolute Error (MAE), and Root Mean Squared Error (RMSE). The analysis of the importance of the features was carried out to determine the most effective parameters that influence the concrete durability, and the analysis revealed that fiber content, fiber type, and fiber length are the most significant parameters.

The digital model was also used to consider different fiber combinations and determine the best-performing combinations in regards to the relative forecasted freeze-thaw resistance. Predicted and measured values were compared, and this proved the model to be reliable and provided the opportunity to evaluate the contribution of each fiber parameter relative to another one. This strategy offered a combined platform to determine the strengths of fiber-reinforced concrete in long-term durability, where real-world information could be offered on which type of fiber and content could be used to enhance the performance of the concrete under freeze-thaw circumstances. The predictive model supplements the laboratory analyses and is a decision support tool in the designing of the concrete that will be more resistant to thawing and freezing.

3 RESULTS AND DISCUSSIONS

The freeze-thaw resistance of an ordinary concrete specimen was discovered to be 160 freeze-thaw cycles. With the specimens randomly reinforced with basalt fibers, the cycles of freezing-thaw reached 180-195 cycles, whereas in the case of specimens reinforced with steel fibers, the cycles were between 190 and 210 cycles. Freeze-thaw resistance in this work was specified, relying on the number of cycles after which the mass loss of the specimen would be 5%.

The freeze-thaw performance of fiber-reinforced concrete specimens that were prepared with different contents of basalt fiber (0.1%, 0.2%, and 0.3%) and fiber lengths (10 mm, 20 mm, and 30 mm) was relatively examined. The freeze-thaw resistance of the ordinary (non-fiber reinforced) concrete specimen is the horizontal line at 160 cycles in the graph. With this reference line, the effect of the enhancement in freeze-thaw resistance of each reinforced combination can be observed by comparing the specimens that are reinforced with the reference line.

As shown in Figure 3, the best performance was achieved using the specimens of 0.2% basalt fiber of length 30 mm with 195 freeze-thaw cycles and this is 21.9 % higher than of ordinary concrete. In the case of specimens reinforced using 10 mm basalt fibers, the freeze-thaw cycle was 176 cycles with a fiber content of 0.1%, 181 cycles with a fiber content of 0.2%, and 184 cycles with a fiber content of 0.3%. The freeze-thaw resistance was increased to 179 cycles at 0.1, 185 cycles at 0.2, and 187 cycles at 0.3 fiber content with the addition of 20 mm basalt fibers.

As shown in Figure 4, specimens that were reinforced with polypropylene fibers had a higher freeze-thaw resistance compared to normal concrete. The series of 0.1% polypropylene fibers 10 mm in length, namely the PP-0.1-10 series, recorded 173 cycles; the PP-0.2-10 series recorded 176 cycles, and the PP-0.3-10 series recorded 180 cycles. The freeze-thaw cycles rose by 8.1-12.5% when compared to normal concrete using 10 mm fibers. The growth rate of 20 mm fibers was 10.6-15.6, and the growth rate of 30 mm fibers was 10.0-19.4%.

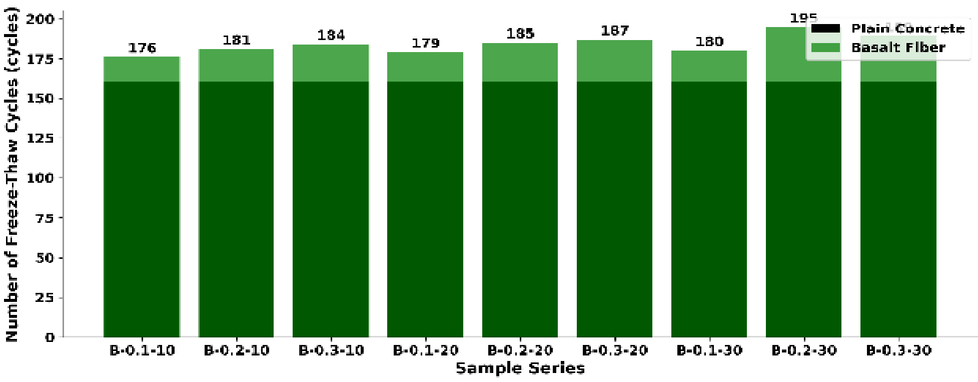

Figure 3: Number of freeze-thaw cycles of fiber concrete dispersed reinforced with basalt fibers.

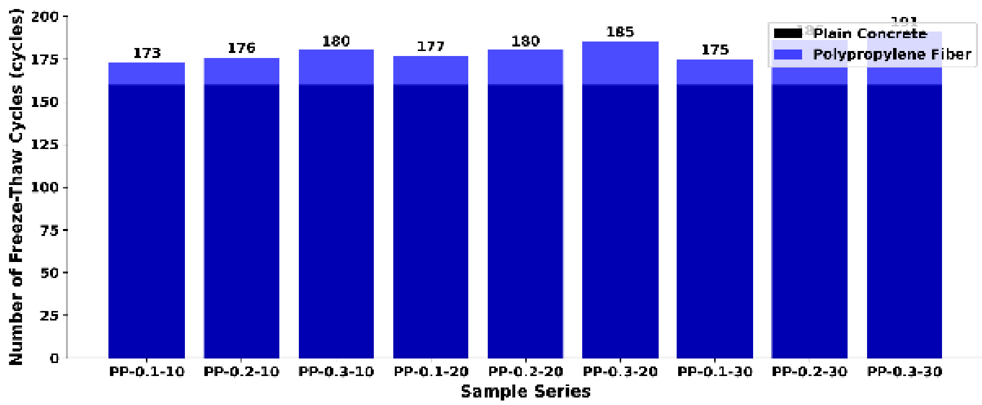

Figure 4: Number of freeze-thaw cycles of fiber concrete dispersed reinforced with polypropylene fibers.

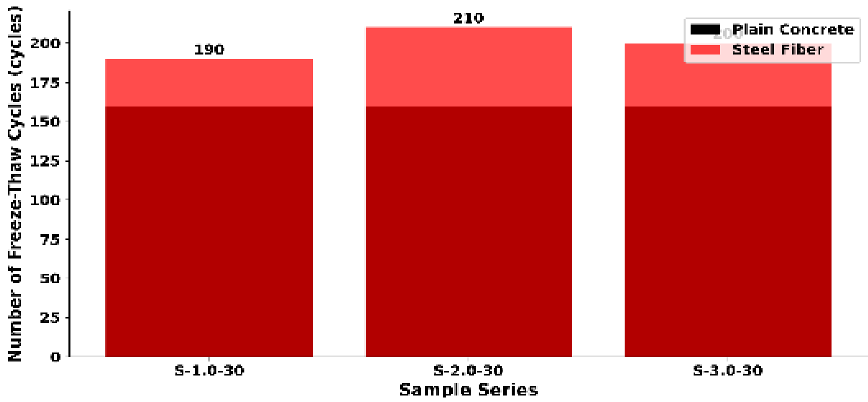

Figure 5: Number of freeze-thaw cycles of fiber concrete dispersed reinforced with steel fibers.

As shown in Figure 5, based on the experimental findings, specimens reinforced with steel fibers exhibited a significant improvement in freeze-thaw resistance compared to normal concrete. The mean freeze-thaw cycles of regular concrete were 160, while the steel fiber-reinforced specimens showed the following: S-1.0-30 series – 190 cycles, S-2.0-30 series – 210 cycles, and S-3.0-30 series – 200 cycles. Therefore, the freeze-thaw resistance increased by 18.8–31.3% relative to ordinary concrete.

To supplement the experimental study, a predictive analysis based on IT implementation was conducted with the help of a Random Forest Regression (RFR) model in order to predict the freeze-thaw cycles of fiber-reinforced concrete on the basis of fiber type, content, length, and series classification. The experimental data of fiber-reinforced concrete cubes are shown in Table 2.

To train the Random Forest Regression model, categorical features (fiber type, series ID) were encoded with one-hot, and numerical features (fiber content, length) were left untouched, and the dataset was divided into 80 percent training and 20 percent testing. Figures 6 and 7 demonstrate the accuracy and reliability of the model because the top 10 fiber combinations and the predicted and actual freeze-thaw cycles have been presented.

The trained Random Forest model had high predictive accuracy with an R^2 of 0.9595 on the test dataset, a mean absolute error (MAE) of 1.631, and a root mean squared error (RMSE) of 1.816. These findings indicate that the model has great potential for predicting freeze-thaw cycles with high accuracy, which is vital in its application in the practical sense of structural engineering, where accurate prediction of durability is needed. In order to estimate the model strength and cross-validation, the five-fold cross-validation was conducted and generated a mean R^2 of 0.9648 (SD=0.0159), a mean MAE of 1.364 (SD=0.164), and a mean RMSE of 1.628 (SD=0.159). The low standard deviations are a sign of consistency in performance between folds, which shows that the model is reliable in forecasting durability in different experimental conditions.

Table 2: Experimental data of fiber-reinforced concrete cubes.

Mix ID	Fiber Length (mm)	Fiber Content (%)	Number of Specimens (n)	Cycles to 5% Mass Loss (mean ± SD)
O	-	0	5	160 ± 2
B-0.1-10	10	0.1	5	176 ± 3
B-0.2-10	10	0.2	5	181 ± 3
B-0.3-10	10	0.3	5	184 ± 2
B-0.1-20	20	0.1	5	179 ± 2
B-0.2-20	20	0.2	5	185 ± 3
B-0.3-20	20	0.3	5	187 ± 2
B-0.1-30	30	0.1	5	180 ± 3
B-0.2-30	30	0.2	5	195 ± 2
B-0.3-30	30	0.3	5	188 ± 3
PP-0.1-10	10	0.1	5	173 ± 2
PP-0.2-10	10	0.2	5	176 ± 2
PP-0.3-10	10	0.3	5	180 ± 3
PP-0.1-20	20	0.1	5	177 ± 3
PP-0.2-20	20	0.2	5	181 ± 2
PP-0.3-20	20	0.3	5	185 ± 3
PP-0.1-30	30	0.1	5	176 ± 2
PP-0.2-30	30	0.2	5	183 ± 2
PP-0.3-30	30	0.3	5	191 ± 3
S-1.0-30	30	1.0	5	190 ± 3
S-2.0-30	30	2.0	5	210 ± 2
S-3.0-30	30	3.0	5	200 ± 3

As shown in Figure 6, the 10 optimal fiber combinations predicted by the Random Forest model were identified to maximize freeze-thaw resistance. The longest predicted cycle life of 210.378 cycles was obtained for steel fibers with 2.0% content and 30 mm length. Other high-performing combinations, particularly those with 3.0% content, reached 199.426 cycles, demonstrating the model's capability to guide material optimization more efficiently than conventional trial-and-error approaches.

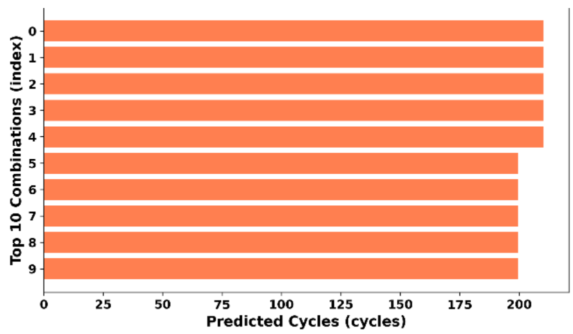

Figure 6: Top 10 Optimal fiber combinations predicted by the random forest model.

Besides, a scatter plot of the predicted cycles versus the actual cycle confirmed the validity of the model, and the predictions were almost similar to the actual experimental values. The best combinations of fibers, as projected by the Random Forest model, are shown in Figure 7, which shows the best predicted freeze-thaw resistance values.

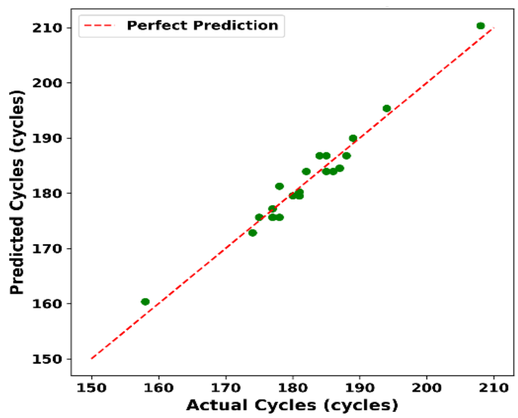

Figure 7: Predicted vs actual freeze-thaw cycles.

This predictive technique enables making decisions based on the data, and it allows the engineers and researchers to choose the most efficient combination of fibers without engaging in a tedious laboratory experiment regarding each combination. The combination of machine learning and experimental confirmation makes this study an important contribution to IT, which alters the conventional civil engineering study into a hybrid framework in which computational modeling is an addition and enhancement of the experimental process.

4 CONCLUSIONS

The freeze-thaw stability of basalt, polypropylene, and steel fiber reinforced concrete was studied in the current research. Using the outcomes of the experiment, the following conclusions can be made:

1) The incorporation of the fibers greatly enhanced the number of freeze-thaw cycles that the concrete specimens were able to withstand prior to failure. The average of plain concrete was 160 cycles, with basalt fiber reinforced specimens having an average of between 176 and 195 cycles depending on the fiber content and length. Polypropylene fiber reinforcement increased the durability by 8-19 percent, whereas steel fiber reinforcement experienced the greatest increase of 18.8-31.3

percent of freeze-thaw resistance over plain concrete.

2) The steel fibers recorded the strongest effect on freeze-thaw resistance when compared to basalt and polypropylene fibers, which were the other types of fibers tested. The most promising results were found to be with 2.0 % steel fiber content, 0.2 % basalt fiber content, and 20-30 mm polypropylene fiber length, which means that the dosage of fibers and geometry of fibers are important factors to consider in increasing durability.
3) It is shown that dispersive fiber reinforcement is a useful technology that can be used to enhance the freeze-thaw performance of concrete, which is especially applicable in the infrastructure of cold areas. It can be noted that optimization of fiber type, content, and length can greatly contribute to service life and minimization of cost of maintenance of concrete structures that are exposed to harsh environments.
4) The combination of the Random Forest Regression modeling offered a powerful digital workflow of forecasting freeze-thaw cycles to allow engineers to choose the best fiber combinations without performing tedious lab work. The analysis of the importance of features identified fiber type and content as the most significant ones. The model attained high predictive power, and the cross-validation indicated its reliability.

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