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Research Article

Statistical Analysis of the Tensile Strength of Coal Fly Ash Concrete with Fibers Using Central Composite Design

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The influence of coal fly ash and glass fiber waste on the tensile strength of cement concrete was studied using central composite design. Coal fly ash was used to replace 10% of the cement in the concrete mix. Glass fiber was added to improve the tensile properties of the concrete in different dosages and lengths. In total, 14 mixes were investigated, one only with 10% coal fly ash replacement of cement and the other thirteen were determined by the experimental design. Using analysis of variance, the order of importance of the variables was established for each property (flexural strength and split tensile strength). From the nonlinear response surfaces, it was found that higher values of flexural strength were obtained for fibers longer than 12 mm and at a dosage of 1-2%. For split tensile strength, higher values were obtained for fibers with a length of 19–28 mm and at a dosage of 1–1.5%.

1. Introduction

Currently, wastes are a major problem throughout the world, as they are stored on huge areas of land and pollute the environment. The capitalization of waste is difficult because of their variety, as well as their unknown properties over time. The building material industry is a domain of interest for wastes, as researchers have tried to produce new construction materials incorporating otherwise useless materials. Many construction materials used today are fabricated with different types of wastes such as concrete, cement, masonry block, and insulating materials [1–5].

An important use for wastes is introducing them as a powder or filler in the composition of construction materials (cement, concrete, asphalt, etc.) or use as aggregates (concrete or bricks from demolition can be used as an aggregate, steel slag can be transformed into aggregates, etc.). Concrete is one type of building material that can incorporate many types of waste such as silica fume, coal fly ash, cinder, husk, tires, and glass [2, 3, 6–9].

The addition of wastes to concrete can improve or diminish some properties of the material [10]. Therefore, a combination of wastes is often used or other materials are introduced into the composition to compensate for any disadvantages. These materials can be fibers of different types or lengths (steel, glass, polyester, carbon, bore, textile, etc.) [11–14] or nanomaterials (nanotubes of carbon, nanoargillaceous materials, etc.) [15, 16].

The present study investigated the tensile properties of cement concrete following the incorporation of coal fly ash

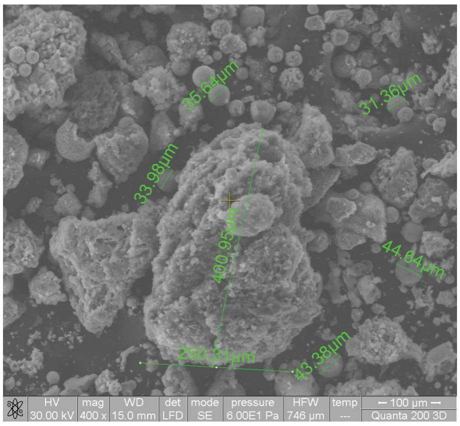

Figure 1: Scanning electron microscopic image of the coal fly ash from the Holboca Thermal Power Plant (magnified 400x).

and glass fiber. Statistical analysis based on central composite design was used to establish the influence of concrete components on its flexural and split tensile properties.

Table 1: Chemical properties of the coal fly ash from thermal power plant Holboca.

	Coal fly ash	
Element	Wt%	At%
CK	17.15	26.89
NK	01.34	01.80
OK	37.50	44.13
NaK	00.69	00.56
MgK	00.52	00.40
AlK	13.09	09.14
SiK	18.37	12.32
SK	00.70	00.41
KK	01.74	00.84
CaK	03.17	01.49
TiK	01.71	00.67
FeK	04.01	01.35
Matrix	Correction	ZAF

Note: Wt is mass percentage and At is the atomic number; K represents the layer to which the chemical properties were determined.

2. Materials and Methods

2.1. Materials. The experimental study was carried out on cement concrete with coal fly ash and glass fibers. To prepare the concrete, the following raw materials were used: cement, ash as a filling agent, river aggregate and gravel, and glass fibers. The cement was type CEM I 42.5, which is a Portland cement produced in Romania.

The coal fly ash (CFA) was from the Holboca Thermal Power Plant, Iasi County, Romania. The ash was an inorganic residue derived from the combustion of pulverized charcoal in the process of generating thermal energy [17, 18]. The coal fly ash was composed of very small round particles, with amorphous glass and crystalline phases; the diameter varied from 0.01 to 400 μm (Figure 1).

The principal properties of coal fly ash were gray-black color, spherical particles, specific area 480–520 m^2/kg, and density 2400–2550 kg/m^3 [18]. The coal fly ash presented pozzolanic properties, that is, a high lime binding capacity, which makes it useful in the manufacture of cement, concrete, and concrete-admixed products. The characteristics of the coal fly ash used in the experimental tests are given in Table 1.

Different lengths of glass fibers were introduced into the concrete mix in different dosages. The fiber percentages were between 0.25% and 1.75% of the concrete weight. The fiber length was between 5 mm and 35 mm. The properties of glass fibers were yarn strength 72.6 N and loop strength 101.85 N. The aggregate was a type of natural sand (diameter 0–4 mm) and river gravel, diameters of 4–8 mm and 8–16 mm. A superplasticizer type Viscocrete-1040 was added to the mixture to improve its workability.

2.2. Experimental Samples. In the study of a new material, there are many factors which influence its behavior under loading and also its durability over time. The factors which could influence the mechanical proprieties of concrete are presented as a fishbone diagram in Figure 2.

The mechanical properties of concrete are affected by various parameters such as the aggregate, water, cement, and additional materials. In the present study, the influence of coal fly ash and glass fiber on the tensile properties of cement concrete was evaluated. The coal fly ash content was maintained constant, 10%, only the dosage and length of glass fibers were varied.

The control concrete composition was grade C25/30: cement 360 kg/m^3 (of which 10% was replaced with coal fly ash), diameter 0–4 mm in a quantity of 803.16 kg/m^3, diameter 4–8 mm in a quantity of 384.12 kg/m^3, diameter 8–16 mm in a quantity of 558.72 kg/m^3, water 180 L/m^3, and superplasticizer type Sika ViscoCrete-1040 in a dosage of 1.4% of the cement weight. Near the control mix, a number of 13 mixes were established by using a rotated centered composed program of second order, with two variables. The total number of tests was statistically established taking into account the number of independent variables, the type of analyze that was done and the type of experimental plan that was chosen. Two variables for input were chosen: length and dosage of glass fiber. The dosages of glass fibers were between 0.25% and 1.75% of the concrete mass, and the lengths were between 5 mm and 35 mm. The experimental matrix contains a number of 13 experiments (13 mixes).

The concrete was prepared in a 1.0 m^3 mixer by mixing the aggregates with cement, coal fly ash, and water; before the final mixing, the fibers were introduced into the fresh mix. The concrete was poured into molds of 100 × 100 × 550 mm and kept in water under laboratory conditions at 20°C. The samples were tested for flexural strength and split tensile strength after 28 days [19].

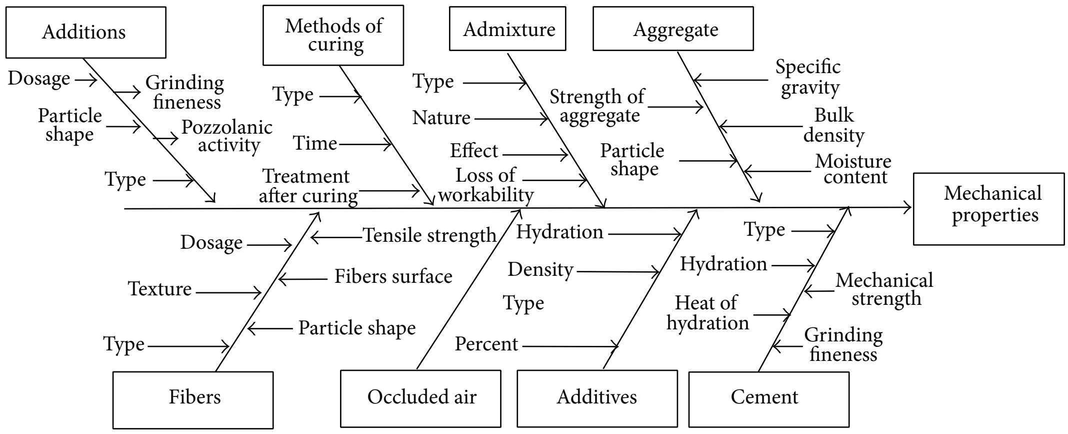

Figure 2: Fishbone diagram of factors affecting the mechanical properties of concrete.

2.3. Design of Experiment (DOE) and Response Surface Method (RSM). RSM consists of a group of empirical techniques devoted to the evaluation of relations existing between a cluster of controlled experimental factors and the measured responses, according to one or more selected criteria. Prior knowledge and understanding of the process and the process variables under investigation are necessary to achieve a realistic model.

RSM provides an approximate relationship between a true response, Y_t, and n design variables, which is based on the observed data from the process or system. The response is generally obtained from real experiments or computer simulations, and the true response Y_t is the expected response. Thus, computer simulations were performed in this paper. We suppose that the true response Y_t can be written as

$$Y_t = F(x_1, x_2, \ldots, x_n), \quad (1)$$

where the variables $x_1, x_2, \ldots, x_n$ are expressed in the natural units of a measurement, so they are called natural variables.

The experimentally obtained response Y_t differs from the expected value y due to random error. Because the form of the true response function F is unknown and perhaps very complicated, we must approximate y. It can be written as

$$y = F(\varsigma_1, \varsigma_2, \ldots, \varsigma_n) + \varepsilon, \quad (2)$$

where ε denotes the random error, which includes the measurement error on the response and is inherent in the process or system.

The variables $\varsigma_1, \varsigma_2, \ldots, \varsigma_n$ are the coded variables of the natural variables. We treat ε as the statistical error, often assuming it to have a normal distribution with mean zero and variance σ^2.

In many cases, the approximating function F of the true response y is normally chosen to be either a first-order or a second-order polynomial model, which is based on Taylor series expansion.

In general, the second-order model is

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum_{j=1}^{k} \beta_{jj} x_j^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j. \quad (3)$$

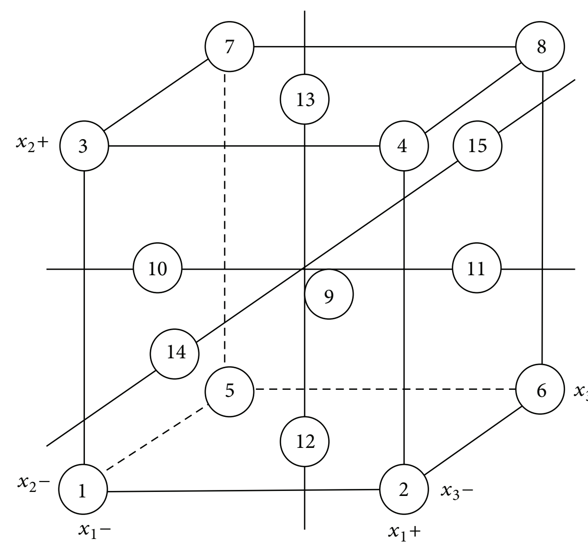

Figure 3: Central composite design for three factors.

In order to more accurately predict the response, the second-order model is used to fit a curvature response at this paper.

Box and Wilson [6] devised a workable alternative to the 3^k factorial system through the development of the class of composite design; this special type of experimental design is called central composite design [6, 7, 14]. Central composite design (CCD) is a 2^k factorial or fractional factorial augmented by an additional axial point and center point. When k is 3, the experimental treatment of CCD is as shown in Figure 3. These eight corner points are located at the vertices of a cube, which in experiments include trials 1, 2, 3, 4, 5, 6, 7, and 8, and are used to develop the first-order model. These experiments are extended to obtain a second-order model. Six axial points and a center point are added to the cube. This design provides five levels for each design variable. Therefore, the number of treatments is calculated by

$$T = 2^k + 2k + n_0, \quad (4)$$

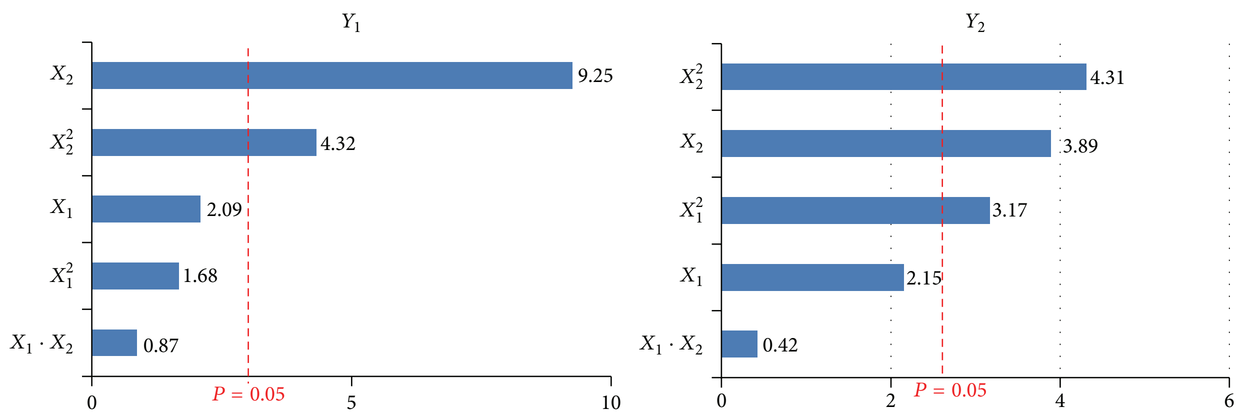

FIGURE 4: Pareto charts of Y_1 (flexural strength) and Y_2 (split tensile strength).

where 2^k is the number of experiments for the 2^k factorial design, $2k$ is the number of axial points, and n_0 is the number of replications for the center point.

In an experiment to predict the response of a system, it is often convenient to use the coded value of a design variable, with −1 representing the low level of a variable and +1 the high level. The coded values of design variables that are obtained from the transforming equation are as follows:

$$\varsigma_i = \frac{x_i - x_{i0}}{d_i}, \quad (5)$$

where x_i is natural variable (length and percentage of fibers) in their original units, ς_i is the coded value of its natural variable, x_{i0} is the natural value corresponding to the zero level, and d_i is equally spaced between the levels of each variable.

2.4. Parameter Selection. To study the influence of concrete components on the tensile strength, 13 mixes were established by the experimental design. In addition to the 13 mixes, a control mix with only coal fly ash (which replaced 10% of the cement) was poured. After testing, the experimental results obtained for flexural strength (f_{ti}), noted Y_1, and splitting strength (f_{td}), noted Y_2, in Table 3 were analyzed using central composite design. All experimentally obtained values of flexural strength and split tensile strength for cement concrete with coal fly ash and glass fibers were greater than those from the cement concrete with coal fly ash (without fibers); that is, $f_{ti} = 3.09\,\text{N/mm}^2$ and $f_{td} = 3.71\,\text{N/mm}^2$. The increase in flexural strength (medium value) by adding glass fibers was about 25% and that of split tensile strength was about 20%.

Table 2 shows the parameters selected for the study, that is, the length of fibers (X_1) and glass fiber percentages (X_2), with their real values as well as the codes used in the central composite design. Table 3 shows the design matrix in coded values.

TABLE 2: Coding of the input parameters.

Parameter	Symbol	Level				
		−1.41	−1	0	1	+1.41
Length	X_1	5	10	20	30	35
Percentage	X_2	0.25	0.5	1	1.5	1.75

TABLE 3: The design matrix in coded values of the CCD.

Runs	X_1	X_2	Y_1	Y_2
1	1.00	1.00	4.12	3.42
2	1.00	−1.00	2.54	2.05
3	−1.00	1.00	3.92	3.02
4	−1.00	−1.00	2.71	2.09
5	−1.41	0.00	3.36	2.48
6	1.41	0.00	4.18	4.43
7	0.00	−1.41	2.34	1.77
8	0.00	1.41	4.32	4.21
9	0.00	0.00	3.91	4.41
10	0.00	0.00	3.98	4.52
11	0.00	0.00	3.89	4.39
12	0.00	0.00	3.95	4.45
13	0.00	0.00	3.93	4.43

3. Results and Discussion

DOE is a structured, organized method that is used to determine the relationship between the different factors (X_i) affecting a process and the output of that process (Y_i). This method and statistical analysis allowed us to investigate the effects of factors on the mechanical characteristics of concrete.

From the experimental tests, the maximum value of flexural strength was obtained for a fiber length of 20 mm and 1.75% glass fiber. The maximum value of split tensile strength was obtained for a length of fiber of 20 mm and 1% glass fiber (Table 3).

Table 4: ANOVA of flexural strength and split tensile strength.

	Y_1					Y_2				
	SS	df	MS	F	P	SS	df	MS	F	P
X_1 (L)	0.18677	1	0.18677	4.0929	0.0828	1.26956	1	1.269	4.620	0.0686
X_1 (Q)	0.13010	1	0.13010	2.8510	0.1352	2.77308	1	2.773	10.09	0.0155
X_2 (L)	3.90324	1	3.90324	85.533	0.0001	4.17901	1	4.179	15.20	0.0059
X2 (Q)	0.85295	1	0.85295	18.691	0.0035	5.10799	1	5.107	18.59	0.0035
X_1 (L) by X_2 (L)	0.03422	1	0.03422	0.7499	0.4152	0.04840	1	0.048	0.1761	0.6873
Error	0.31944	7	0.04563			1.92339	7	0.2747		
Total SS	**5.33507**	**12**				**14.15548**	**12**			

Table 5: Observed, predicted, and residual values of the two responses Y_1 and Y_2.

	Y_1			Y_2		
	Observed	Predicted	Residual	Observed	Predicted	Residual
1	4.12	4.390851	−0.270851	3.42	4.238635	−0.818635
2	2.54	2.850557	−0.310557	2.05	2.616282	−0.566282
3	3.92	3.909381	0.010619	3.02	3.245694	−0.225694
4	2.71	2.739087	−0.029087	2.09	2.063341	0.026659
5	3.36	3.414341	−0.054341	2.48	2.523305	−0.043305
6	4.18	3.859047	0.320953	4.43	3.682717	0.747283
7	2.34	2.180224	0.159776	1.77	1.586246	0.183754
8	4.32	4.213165	0.106835	4.21	3.689776	0.520224
9	3.91	3.918669	−0.008669	4.41	4.404801	0.005199
10	3.98	3.918669	0.061331	4.52	4.404801	0.115199
11	3.89	3.918669	−0.028669	4.39	4.404801	−0.014801
12	3.95	3.918669	0.031331	4.45	4.404801	0.045199
13	3.93	3.918669	0.011331	4.43	4.404801	0.025199

To continue the study, it was important to determine which parameter had the greatest influence on strength. This parameter was then varied to obtain higher values for the flexural strength and split tensile strength.

Analysis of variance (ANOVA) is a common method used to compare the relative strength of two related models. This method analyzes the degree to which residual variance changes with the addition of explanatory variables to the basic model. ANOVA (Table 4) gives a nonlinear response surface with the significant factor X_2 for the two responses, Y_1 and Y_2. This is shown by the value of P (Table 4), which must be very small; that is, $P < 0.05$.

Pareto charts [6, 7, 14] obtained from the statistical analysis are presented in Figure 4, and show the importance order of the variables. Consequently, it can be seen that X_2 (fiber percentage) was the factor that most significantly influenced the response Y_1, through its linear and nonlinear components; X_1 (fiber length) did not influence Y_1. Also, Y_2 was significantly affected by X_2 (fiber percentage), by its linear and nonlinear components, and by the length of the fibers (X_1), through the nonlinear component.

The predicted values in Table 5 were obtained by regression with an error of 0.05%. The coefficient of determination, R^2, is given by $R^2 = 0.94012$, for Y_1, and $R^2 = 0.86412$ for Y_2, which indicate a good approximate for the two responses.

In this study, three-dimensional response surface plots were constructed to illustrate the effect of any two factors (X_1, X_2) on the two response values Y_1 (flexural strength) and Y_2 (split tensile strength). Figure 5 illustrates the nonlinear response surface model of the length versus the percentage of fibers obtained with the Matlab program.

In Figure 6, it can be seen that higher values of Y_1 (flexural strength) were obtained for a length greater than 12 mm and for an incorporation percentage of 1-2%. For Y_2 (split tensile strength), higher values were obtained for a length of 19–28 mm and an incorporation percentage of 1–1.5%.

4. Conclusions

This study focused on characterizing cement concrete containing coal fly ash and glass fiber. Coal fly ash was used to replace a part of cement and glass fiber was added to improve the mechanical properties, especially the tensile strength. The statistical analysis showed that higher values of Y_1 (flexural strength) were obtained for a fiber length greater than 12 mm and an incorporation percentage of 1-2%. For Y_2 (split tensile strength), higher values were obtained for a fiber length of 19–28 mm and an incorporation percentage of 1–1.5%. The optimum value for both strengths was obtained with an

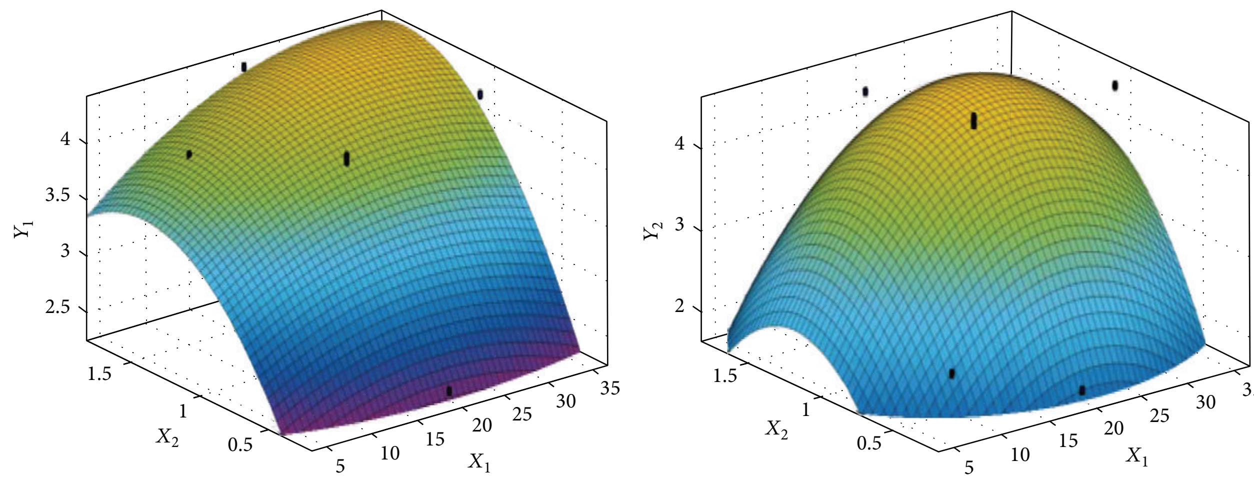

FIGURE 5: Response surface for flexural strength, Y_1, and split tensile strength, Y_2.

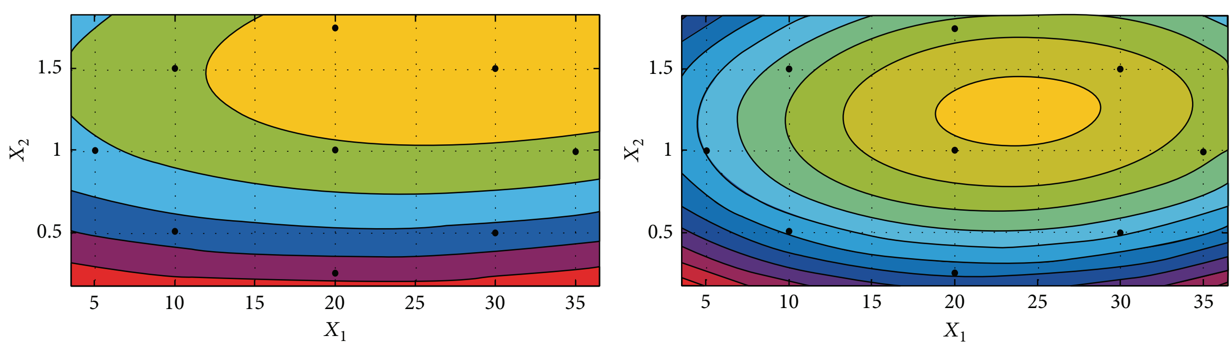

FIGURE 6: Contour plot for Y_1, flexural strength, and Y_2, split tensile strength.

incorporation percentage of 1–1.5%, but not for the same length of fiber. This study showed that wastes can be used as supplements or replacements for cementitious materials, even if they do not improve all characteristics. This depends on the properties of interest, as other materials, such as fibers, can be combined to obtain useful construction materials.

Conflict of Interests

All authors declare that there is not any conflict of interests in this paper.

Authors' Contribution

All authors contributed to and approved this paper.

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