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COMPRESSIVE TOUGHNESS AND EMPIRICAL MODELLING OF NATURAL FIBER REINFORCED SILICA FUME BASED CONCRETE

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Abstract- The use of natural fiber is increasing day by day because it is an economical and waste material as well as has advantages from the environmental aspects. Among the natural fibers, coconut fibers (CF) have the maximum toughness. The addition of supplementary cementitious materials like silica fume together with coconut fiber will lead to complementary benefits in terms of mechanical performance and environmental aspects. Additionally, the establishment of an empirical equation will be helpful for the researchers to predict the experimental stress-strain response. Therefore, in this study, the control mix, silica fume concrete, coconut fiber reinforced concrete, and coconut fiber reinforced silica fume based concrete are investigated for compressive toughness and empirical modeling. Furthermore, scanning electron microscopy (SEM) is also performed to study the microstructure of the matrix. It was found that the addition of coconut fiber and silica fume in the matrix improved the compressive toughness and microstructure of concrete. In addition, the stress-strain curves obtained from the empirical equation showed the goodness of fit with the experimental data.

Keywords- Coconut fiber, silica fume, concrete, compressive toughness, empirical modeling.

1 Introduction

In agriculturally progressive countries, natural fibers and plant fibers are available abundantly. These fibers can produce environmentally friendly materials when added to the concrete as reinforcement. Fibers added to the concrete tend to enhance the concrete performance such as energy absorption capacity, post cracking response, strength, etc [1-4]. As a plant residual waste, natural fibers have a significant economic value because of their use in construction materials all over the world. Natural fibers have the potential to reduce the quantity of basic ingredients in various composite materials that leads to environmentally friendly material. As compared to synthetic fibers, natural fibers contribute with the same properties when added to composites in terms of strength against shear, tension, temperature, and impact. The disadvantages of concrete that can be improved include the brittle behavior, low tensile strength, less resistance to cracks occurrence and propagation. The uniformly distributed fibers in the matrix play an important role in the improvement of concrete properties. Additionally, the incorporation of fibers in composites helps in controlling cracks [5]. The use of natural/plant fibers in building materials is from the Biblical times (approximately 3500 years ago) e.g. in clay sun-baked bricks [6]. Natural fiber is an economical and waste material, so it has also advantages from the ecological aspects. Among the natural fibers, coconut fibers (CF) have the maximum toughness [7], [8, 9]. The mechanical properties of CF reinforced concrete were investigated by Ali et al. [10]. The best performance was observed with 2% fiber content having 50 mm length. Currently, composites having fibers and mineral admixtures are introduced by the researchers for civil engineering applications [11], [12]. Luther [13] used different contents of silica fume (SF) i.e. from 5-15% in concrete and the best overall results were obtained with 11.5% content of SF by mass of cement. Thus, the combined use of natural fiber together with supplementary cementitious material will be helpful form improve performance of concrete in term of mechanical properties as well as sustainability.

The basic mechanical characteristic for fiber reinforced composites (FRC) is the stress-strain curve that is obtained from the uniaxial compressive load test. For example, an analytical model was developed by Ou et al. [14] for the stress-strain curve from compression test for the concrete reinforced with different sizes of steel fibers. The model was established to characterize the stress-strain behavior of composite with a high reinforcing index. It was reported from the results that the developed analytical model showed good agreement with the experimental results. Li et al. [15] studied the experimental characterization of polyvinyl alcohol engineered cementitious composite (PVA-ECC) established in the form of stress-strain curves. It was reported that PVA-ECCs showed that the established model presented good results with that of experimental results. Wang et al. [16] developed a rational fraction expression that both segments (i.e. ascending and descending) can be expressed by the rational formula. Saber et al. [17] examined the compressive stress-strain performance of high strength concrete (HSC) reinforced with synthetic fibers. The two simple models for the compressive stress-strain curve of the composite were used. It was suggested from the results that, the proposed models are able to predict the experimental results with better precision. Bencardino et al. [18] performed a comparative study on the experimental data of steel fiber reinforced concrete and proposed empirical models for stress-strain relationships. It was found that empirical models showed good agreement with test results. Furthermore, other researchers such as Li et al. [19] and Cao et al. [20] also conducted a comparative study on compressive modeling and reported a good correlation between experimental results and empirical models. Thus, it will be of great interest to develop a model for the composites reinforced with natural fiber for better prediction of experimental data.

The motivation for the current research is to deliver an economical and environmental friendly material to the construction industry using natural fibers. It is a major issue all over the world for sustainable development to manage agricultural waste. If instead of synthetic fibers, natural fibers are used in the construction industry it will result in greener and sustainable development. Lately, the use of natural fibers got special attention in many structural components [10], [21], [22], [7]. The main focus of the current study is the establishment of empirical modeling instead of evaluating material behavior. That is why other properties from the compressive test i.e., peak stress, peak strain, elastic modulus, etc. were not studied. Also, the studies on such material properties of CF reinforced concrete have been reported in the literature [9], [23]. The significance of the present research is to develop a model that can be helpful to predict the experimental results of natural fibers reinforced concrete for a structural design application in civil engineering. In this study, the coconut fiber together with silica fume is studied for the compressive toughness and empirical modelling. In addition, the microstructure of the matrix is also studied by scanning electron microscopy (SEM).

2 Experimental Procedures

2.1 Raw ingredients.

The ingredients used in the present experimental work include CF, SF, cement, coarse aggregate, fine aggregate, and water. The SF was bought from Sika Pakistan Pvt. Ltd. The SF used was as per requirements of ASTM C-1240 [24] and contains a minimum of 85% silicon dioxide (SiO_2) and its specific gravity was 2.26. The maximum size was 12.5 mm for coarse aggregate and the fineness modulus of fine aggregate was 2.7. The length and average diameter of CF used in the current work was 50 mm and 0.3 mm, respectively. The CF of 2% content by mass of cement was used. The reason for selecting the length and content for CF is that most of the literature reported the best performance of CF with 50 cm length and 2% content by mass of cement [10], [7], [25], [26], [27]. The mix design for all the mixes is shown in Table 1. The w/c for CF reinforced concrete was kept relatively higher to achieve proper compaction of the mix along with good workability. At lower w/c of the mix containing CF, proper compaction of the fresh mix was not possible which may result in reduced strength. Since, compaction has more influence on concrete properties, as compared to w/c. A similar approach for the addition of CF in concrete is also reported in the previous studies [10, 23].

Table 1- Mix proportions

Mix Type	Symbols	Cement (Kg/m³)	Sand (Kg/m³)	Aggregate (Kg/m³)	W/C ratio (-)	Silica fume (%)	Coconut fiber (%)
Control mix	CM-SF0	400	810	810	0.45	0	0
Silica fume concrete	CM-SF10	400	810	810	0.45	10	0
Coconut fiber reinforced concrete	CFRC-SF0	400	810	810	0.50	0	2
Coconut fiber reinforced silica fume based concrete	CFRC-SF10	400	810	810	0.50	10	2

Note: All percentages are by mass of cement.

The mixing of all the mixes was done by the layer's method reported by Ali et al. [10]. Cylinders of 100 mm diameter and 200 mm height were cast for compressive properties. A set of two specimens were cast from each mix type and the average of their result was considered in the analysis. A similar practice of using an average of two specimens is also reported in the previous study [28]. The casting and curing of specimens were done following ASTM standard C192M-16a [29]. The compressive strength test of the cylinders was performed following ASTM C39/C39M-17b standard [30]. For the SEM analysis, the samples were taken from the crushed cylinders after performing the compressive strength test.

3 Results

3.1 Compressive toughness.

The toughness and specific toughness (ST) are used to determine the compressive energy absorption capability of concrete. The area under the stress-strain curve is used to calculate the toughness and the ST is calculated as the ratio of compressive toughness to the compressive strength of the same specimen [31]. The best overall performance was obtained when both SF and CF were used in the same mix as shown in Figure 1. The addition of SF in concrete has shown a significant effect on the enhancement of toughness as well as ST. This enhancement is because of filling the pores in the concrete and the pozzolanic reaction caused by SF. Furthermore, the addition of CF also shown a considerable increase in toughness and ST of coconut fiber reinforced composites. This increase in toughness and ST is due to the bridging effect provide by CF under loading.

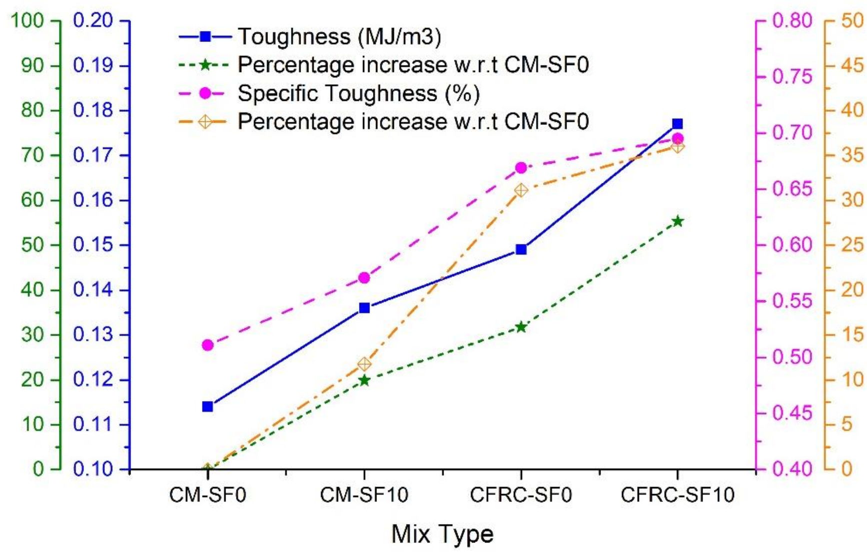


Figure 1: Compressive toughness

3.2 Empirical modeling.

The empirical model is shown in Equation (1) consists of a simple rational power function having parameter A. Figure 2 demonstrates the comparison between normalized stress-strain curves and empirical model curves. The parameter "A" is obtained from fitting the experimental normalized stress-strain curves. The acquired stress-strain curves based on the empirical model are well fitted in accordance with the experimental normalized stress-strain curve. This indicates that the empirical model can obtain a better stress-strain response from the experimental stress-strain curves. The highest correlation coefficients are achieved, i.e. greater than 0.95. This shows that the present model can be applied to predict the response of the compressive stress-strain curve from experimental data.

$$Y = \frac{AX}{A-1+X^A} \qquad (1)$$

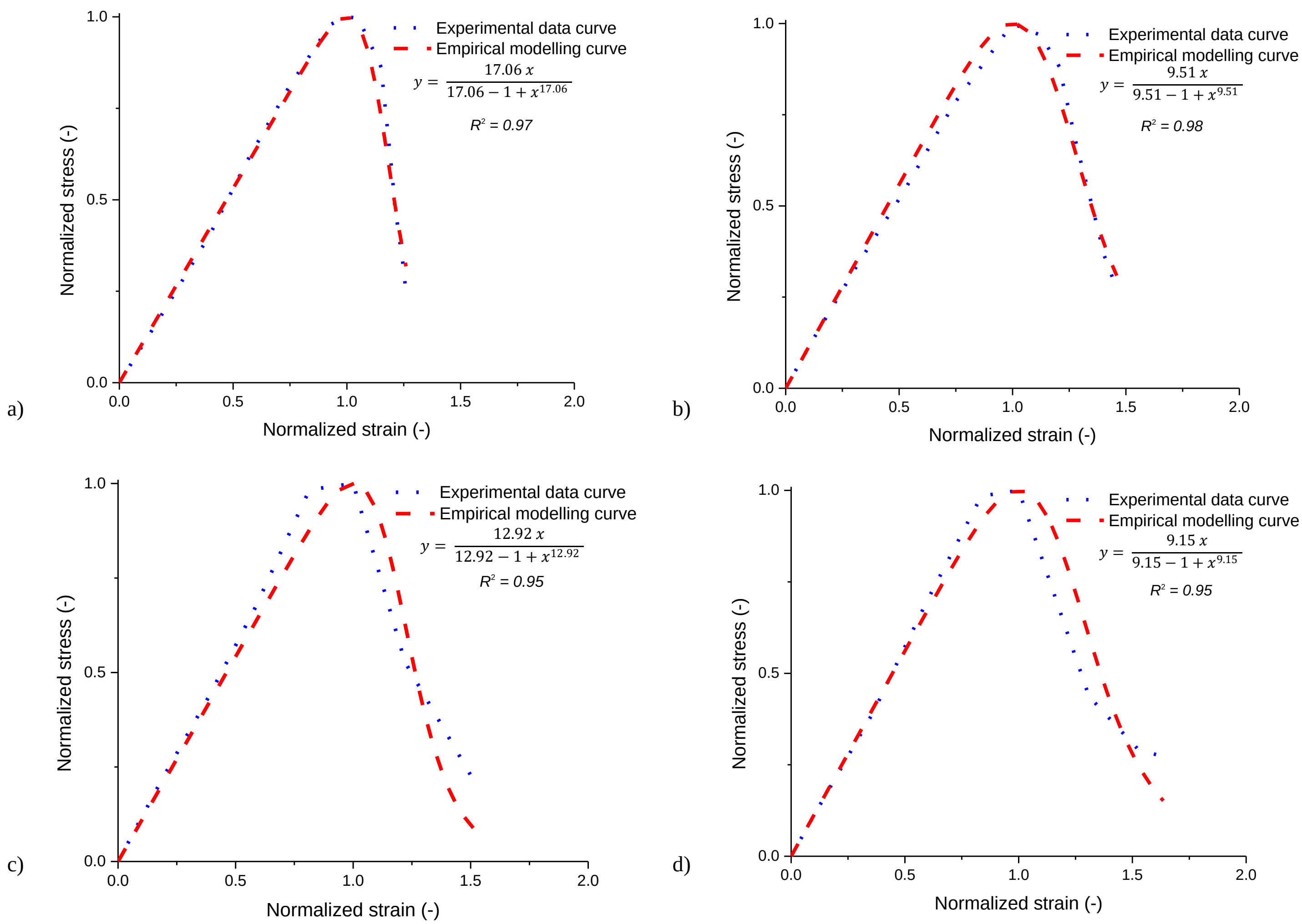
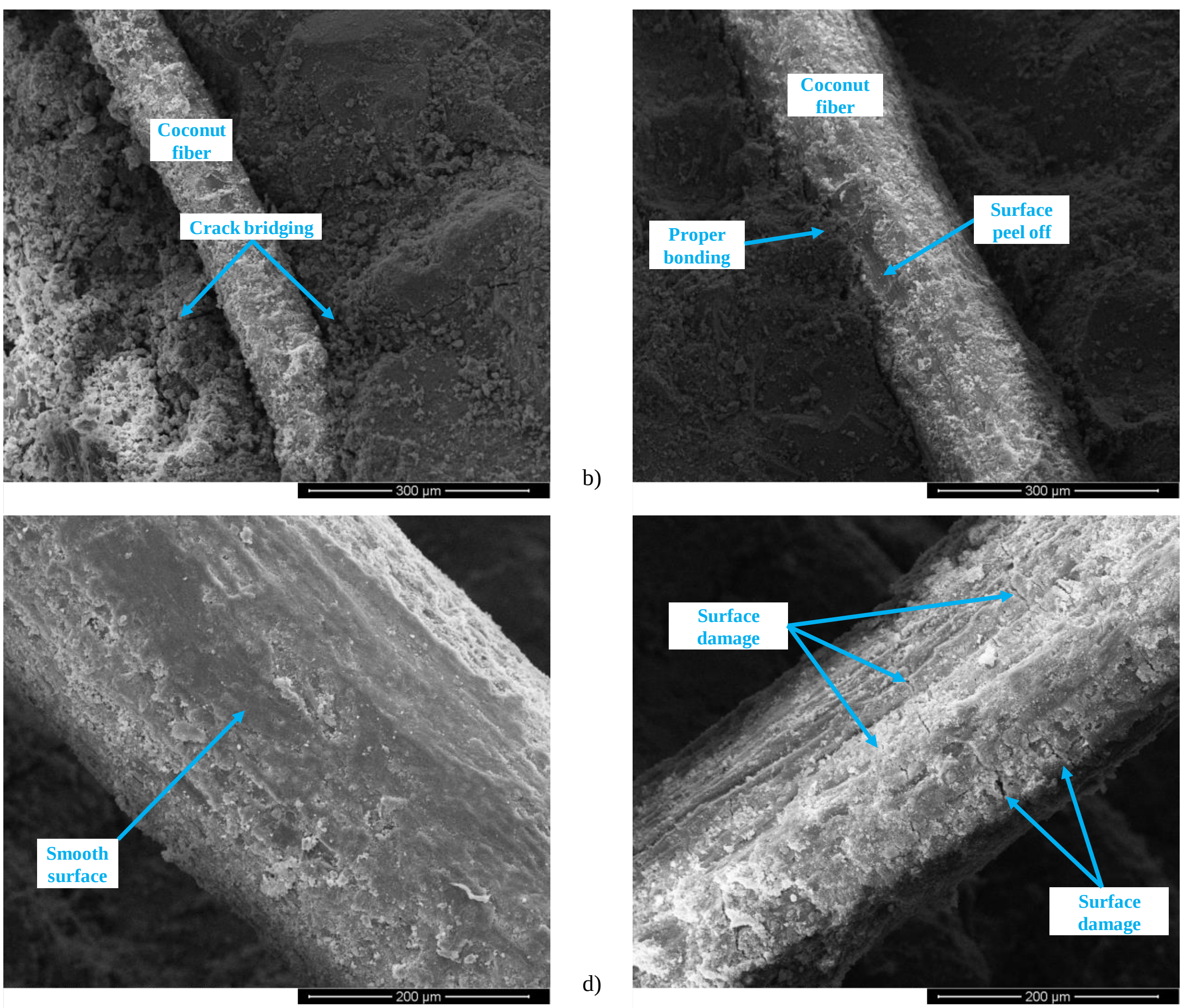


Figure 2: Empirical modelling, a) CM-SF0, b) CM-SF10, c) CFRC-SF0, and d) CFRC-SF10

3.3 Scanning electron microscopy analysis.

SEM analysis was performed to investigate the micro-cracks in the matrix, fiber-cement bonding, cracks in the matrix, and fiber condition before and after pullout from the matrix. The fiber bridging effect due to the incorporation of CF in concrete showed resistance against crack propagation as shown in Figure 3 (a). Also, a proper bond between the CF and matrix can be observed in Figure 3 (b). The SEM images of CF surface before mixing and after pull-out are also presented in Figures 4 (c) and 4 (d), respectively. The surface of CF after pull-out was observed to be damaged. Also, the crack was observed on the surface after fibers pull-out as compared to that of the fiber surface before mixing. The observations of enhanced toughness properties due to CF addition from experimental results were also supported by SEM analysis. Hence, the CF addition in concrete favors its utility to be used in civil engineering applications due to improved performance. The cementitious composites are brittle and there are micro-cracks and voids in the matrix formed during the hydration process. These micro-cracks propagates during loading, become macro-cracks, and ultimately results in the destruction of the structure. So, the failure process starts from the micro-cracks present in the matrix which leads towards material failure. As fibers can provide resistance to the crack propagation by bridging effect. Therefore, fiber addition in the cementitious composites enhanced the mechanical properties of composites by preventing crack expansion. Regarding the damaged surface of coconut fiber, it is recommended for future to develop some treatment methods for the improved surface of coconut fiber that will be beneficial to enhance the bond performance after pull out.

a)


c)

Figure 3: Scanning electron microscopy analysis, a) fiber bridging, b) fiber bonding and surface peel off, c) fiber surface before mixing, and d) fiber surface damage after the pullout

4 Conclusion

In this study, the coconut fiber reinforced silica fume based composites are explored for compressive toughness, empirical modeling, and microstructural analysis. The following conclusion can be drawn:

- The addition of silica fume as well as coconut fiber increased the toughness and specific toughness of concrete.
- The stress-strain curves results obtained from the presented empirical model showed good agreement with the experimental data.
- The SEM analysis showed the fiber bridging, proper bonding, and fiber surface damage and also supported the results of improvement in compressive properties due to the addition of CF in concrete.
- The overall best performance was observed with the addition of both coconut fiber and silica fume in the same mix as compared to that of fiber reinforced concrete reinforced individually with silica fume and coconut fiber.

It is recommended that further studies should be carried out by using more content of CF in concrete for empirical modeling. In addition, it is suggested to investigate the durability of coconut fiber as a concrete fiber reinforcement. Furthermore, the study on the overall pore shape and pore continuity of the coconut fiber material for the concrete application needs to be explored in the future.

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