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An Analytical Linear Model for Hemp-Reinforced Concrete

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ABSTRACT

The current paper reports an analytical linear model of hemp-reinforced concrete. The model data is based on a previous experimental study encapsulating natural industrial hemp fibers in plain concrete mixes, where twelve mixes were considered including one without fibers (control mix), one with polypropylene fibers, and ten with industrial hemp fibers. Specimens prepared with hemp fibers showed similar performance to specimens with polypropylene fibers. The use of industrial hemp fibers allowed the reduction of coarse aggregates while providing ductile flexural performance. Analytical linear models are investigated and are presented in the current paper. The analytical models provided a preliminary estimate of the compressive, flexure, and modulus of elasticity properties of nine different hemp-concrete mixes in terms of the fibers volume fraction, coarse aggregate reduction, and fibers aspect ratio. The linear models' results allow the prediction of the compressive strength, maximum flexure strength, and the modulus of elasticity of hemp-reinforced concrete.

Keywords. Sustainable materials, natural fibers, industrial hemp, fibers volume fraction, aggregate reduction.

INTRODUCTION

The future of our planet depends on the habitat willingness to pursue sustainable actions and developments. In developed nations, governments and general public are committed for the principles of sustainable development. In order to improve the quality of contemporary life without compromising that of future generations, the sustainable development in terms of knowledge, concepts, and practices should extend to all nations irrespective of the nations' economic conditions.

Currently, the construction industry developers worldwide are engaged in finding and creating outmost sustainable solutions for high performance and durable construction materials. One example of sustainable construction materials is natural fiber-reinforced concrete, natural fibers such as bamboo, jute, straw, hemp, and many others. Synthetic and also natural fiber-reinforced concrete date back to 1870s; since then, researchers have tried to counterbalance the weak tensile strength in concrete by the bond provided by the fibers and the concrete matrix (Naaman, 1990).

Fiber-reinforced cement or concrete is a separate and wide field of study, which is beyond the scope of this paper. In the current paper, analytical linear models are considered in order to predict the results of the compressive strength, modulus of elasticity, and flexure tests at 28 days concrete age. The input data for the models are based on the correspondent tests results retrieved from previous experimental studies. The variables considered in the linear models are: fibers volume fraction, coarse aggregate reduction, and fibers aspect ratio.

BACKGROUND

Fiber-reinforced concrete (FRC) is produced by mixing hydraulic cement, aggregates, water, and reinforcing fibers. Synthetic fibers such as steel and polypropylene, or natural fibers such as hemp, sisal, and others may be incorporated. The fibers orientation is random, discrete, and discontinuous. Fiber-reinforced concrete is expected to satisfy the strength, ductility, and durability requirements of a high performance concrete material. FRC has been used in many applications such as slabs on grade, airports and pavements, tunneling, rock stability, and shotcrete works (ACI 544.1R-1996).

International research and accordingly substantial publications have been issued about fiber-reinforced cements and concretes. The addition of fibers strengthens the concrete weak tensile properties and, consequently, the durability of concrete is enhanced. Thus, a more durable concrete mitigates the need for maintenance and rehabilitation activities of old existing concrete and therefore provides a sustainable concrete. In addition to industrial fibers, natural organic and mineral fibers have been also investigated in reinforced concrete; wood, sisal, jute, bamboo, coconut, asbestos, and rockwool are examples of such fibers researched and reported (Zhu, 1994, Al Rim, 1999, Bilba, 2007, and Savastano, 2008).

In a preliminary study, Awwad et al. (Awwad, 2009 and 2010) investigated the behavior of hemp, banana, and palm fibers as concrete composites. Mainly, the flexural and compressive strength of specimens prepared with natural fiber-reinforced concrete were tested. Results showed a ductile behavior of the tested flexural beam specimens. Based on these initial tests results, the use of industrial hemp fibers in concrete mixes indicated promising compression and flexural strength values; it also confirmed the potential of reducing the consumption of coarse aggregates when adding hemp fibers.

In another study (Awwad, 2011 and 2012a), the industrial hemp was subjected to further investigations, where cubes (70 mm), beams (50 x 50 x 200 mm), and standard cylinders

(150 x 300 mm) were prepared and tested. The cylinders compressive strength was determined at 3, 7, and 28 days. Control and polypropylene fibers mixes were included for comparison purposes and validation. It was shown that the addition of both synthetic and natural fibers resulted in a decrease in the compressive strength for cylinder specimens. However, the presence of the hemp fibers associated with reducing the coarse aggregate content resulted in a ductile flexural performance, instead of a brittle failure as in the case of plain concrete with no fibers. The results of the cylinder specimens showed that the fiber content and the coarse aggregate reduction are related; as such, when the coarse aggregate amount is reduced, more space is allowed for the fibers to interact in the concrete matrix, provided the amount of fibers is sufficient. The flexural behavior of fiber-reinforced concrete depends on the matrix and the fibers orientation, especially in the presence of coarse aggregates and small specimen sizes. For fiber-reinforced concrete, the deflections at maximum flexural loads are larger than those of control specimens, indicating a decrease in the stiffness of fiber-reinforced concrete specimens.

In an extensive research (Awwad, 2012b), the physical properties in addition to the thermal characteristics of the newly defined mixes were investigated and reported. The hemp fibers were added in different volumetric percentiles (0.5%, 0.75%, or 1%) of the concrete volume, with a coarse aggregate reduction (10%, 20%, or 30%) of the concrete volume. The flexure and splitting properties in addition to the modulus of elasticity, density, and thermal characteristics were determined. Twelve mixes were prepared. The flexural strength was determined at 7 and 28 days; and all other tests were performed at 28 days. The results reported represent the average of three tested specimens, except for the thermal block test since the thermal conductivity result is an average measured value. In all, a total of 180 cylinders, 72 beams, and 12 blocks were tested and reported (Awwad, 2012b). Based on the standard cylinders tests, the flexure results showed that the presence of hemp fibers allowed coarse aggregate reduction and resulted in a ductile behavior. The splitting tensile results were not affected in the presence of sufficient fibers. The modulus of elasticity results assured the ductility of the hemp concrete mixes. The thermal conductivity results showed the effect of hemp fibers in reducing the heat flow. The slump results were reduced by the hemp fibers water absorption. The density results were slightly decreased with the coarse aggregate reduction. It was concluded that by adding 0.75 to 1.0% hemp fibers to the concrete with 20 to 30% coarse aggregate reduction, a new concrete mix can be produced. Although the new concrete mix may have lower compressive strength by about 25%, a ductile behavior is reached, the material is more flexible with 20 to 30% decrease in the modulus of elasticity, the splitting tensile strength is not affected, and the thermal conductivity is reduced by about 25 to 35%.

According to (Naaman, 1990), researchers started considering analytical models of fiber-reinforced concrete mixes using linear models, and more sophisticated non-linear models were investigated then after (Barros, 1999, Mansur, 1999, and Junior, 2010).

OBJECTIVE

The aim of this paper is to set an analytical model to predict the behavior of hemp-reinforced concrete mixes in terms of compressive, flexure, and modulus of elasticity. Therefore, the validity of such models may substitute the experimental testing on similar hemp-reinforced mixes. The analytical model is linear and preliminary which can be upgraded based on the current output and findings.

ANALYTICAL MODEL

In the current paper, linear models are set and investigated. Based on (Awwad, 2012a and 2012b), linear models are developed in order to predict the compressive strength, modulus of elasticity, and flexural strength of samples tested at 28 days. The different mixes proportions are available in the reference (Awwad, 2012b). The models were developed based on results of the samples tested for 0.5%, 0.75%, and 1.0% hemp volume fractions, and for 10%, 20%, and 30% coarse reductions; i.e., nine (3 x 3) mixes were incorporated in the analytical model.

The linear models consider three variables: the fibers volume fraction (V_f), the coarse aggregate reduction (CR), and the fibers aspect ratio (AR). The values of aspect ratio studied were 40, 50, and 60. However, analysis revealed that the effect of AR was negligible and did not affect the predicted values for compressive strength, modulus of elasticity, and flexural strength. Thus, a fixed value of 50 was adopted in the development of the linear models.

The models required input are the control mix (plain concrete) tests results in order to predict the hemp-reinforced mixes properties in terms of compression, modulus of elasticity, and flexure at 28 days concrete age.

MODELS OUTPUT AND ANALYSIS

The linear models output in terms of compressive strength, modulus of elasticity, and flexural strength are presented and discussed below.

Compressive Strength. Many trials were investigated for the compressive strength linear model in order to optimize the predicted result. The control mix average result used was 23.4 MPa. The sum of square of the error (E^2) between the predicted ($f_{predicted}$) and measured compressive strengths was calculated for all nine mixes. The linear model that minimized the sum of square of the error E^2 the most was selected.

Table 1. Linear Model Trials for Prediction of Compressive Strength.

$f_{predicted}$	E^2	Variables
$144.37 - 5.45\,(f_{control})(1 - V_f/100)$	8.88	V_f only
$16.91 + 0.001(f_{control})(AR)(V_f)$	8.88	AR & V_f
$12.52 + 0.286(f_{control})(1 - CR/100)$	6.82	CR only
$12.58 + 0.285(f_{control})(1 - CR/100)(1 - V_f/100)$	6.88	CR & V_f
$11.53 + 0.288(f_{control})(1 - CR/100)(1 - V_f/100) + 0.0268(AR)(V_f)$	6.21	CR, V_f, & AR

Referring to Table 1, first the only variable included in the model was the volume fraction. The model was not adequate and not sensitive to the volume fraction alone. The aspect ratio was added as another variable along with the volume fraction in the model, but still the model was not adequate and not sensitive to both the volume fraction and aspect ratio. The coarse aggregate reduction separately was also investigated, the model was more sensitive to the coarse reduction than the V_f and AR but still not adequate enough in predicting values close to those measured. A combination of the coarse reduction and fibers volume fraction was investigated. Finally, the optimal linear model was found to be adequate when the coarse reduction, volume fraction, and aspect ratio were all included, as follows:

$$11.53 + 0.288(f_{control})(1 - CR/100)(1 - V_f/100) + 0.0268(AR)(V_f) \qquad (1)$$

where $f_{control}$: the compressive strength test result of the control mix.

Using this model, the sum of the square of the error was minimized to 6.21. The predicted data fitted well around the 45° line when plotted against measured values (Figure 1), which justifies the adequacy of the model.

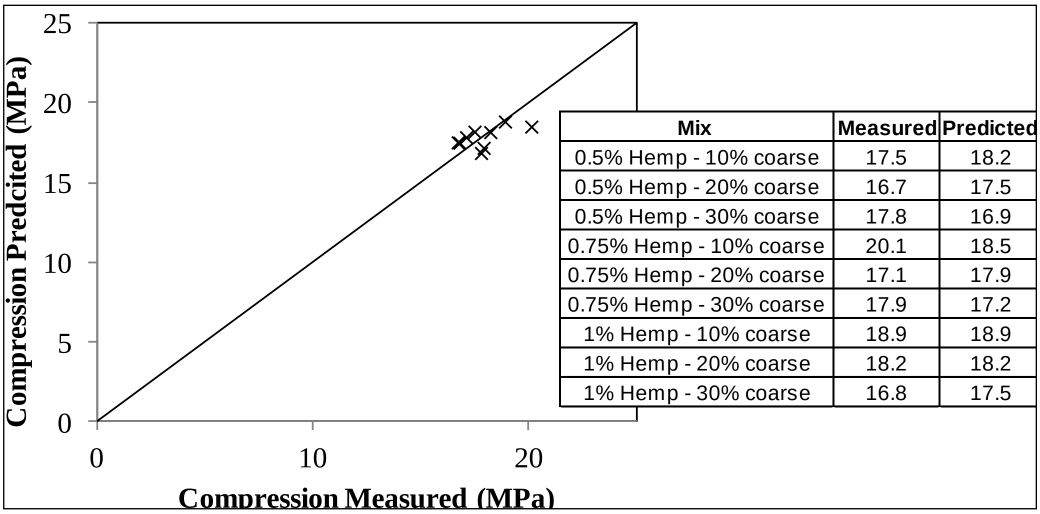


Figure 1. Best Fitted Data for the Compressive Strength Linear Model Incorporating CR, V_f, and AR (Measured Data from Awwad, 2012b).

Modulus of Elasticity. Many trials were investigated for the modulus of elasticity linear model in order to optimize the predicted modulus. The modulus used for the control mix result was 23,754 MPa. The sum of the square of the error (E^2) between the predicted ($E_{predicted}$) and measured moduli was calculated for all nine mixes and the minimum of the sum of the square of the error E^2 was targeted.

Table 2. Predicted Modulus of Elasticity Linear Model Trials (Square Error E^2 is Divided by 10^6).

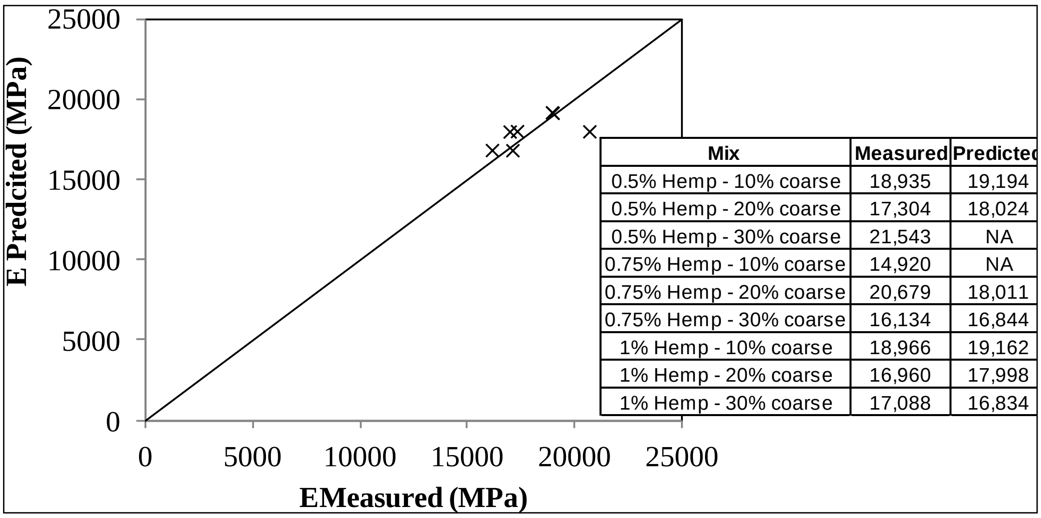
$E_{predicted}$	$E^2/10^6$	Variables
$-929.369 + 0.805(E_{control})(1 - V_f/100)$	36.43	V_f only
$1074.742 + 0.0176(E_{control})(AR)(V_f)$	265.91	AR & V_f
$20650.2 - 0.136(E_{control})(1 - CR/100)$	36.24	CR only
$20536.1 - 0.131(E_{control})(1 - CR/100)(1-V_f/100)$	36.29	CR & V_f
$23068.9 - 0.138(E_{control})(1 - CR/100)(1-V_f/100) - 64.09(AR)(V_f)$	32.44	CR, V_f, & AR
$8641.3 + 0.495(E_{control})(1-CR/100)(1 - V_f/100) + 0.837(AR)(V_f)$	9.39	CR, V_f, & AR

Referring to Table 2, when the volume fraction was only included, the model was not adequate and not sensitive to the volume fraction alone. The aspect ratio was added with the volume fraction in the model, and the model was still not adequate and not sensitive to both the volume fraction and aspect ratio. The coarse aggregate reduction was also investigated separately and the model was still not adequate. A combination of the coarse reduction and fibers volume fraction was investigated. Finally, the optimal linear model was found to be adequate when the coarse reduction, volume fraction, and aspect ratio were all included. The sum of the square of the error was minimized to 32.44 and the data were best fitted. The predicted data fitted well around the 45° line, but two outliers appeared to affect the model adequacy. Thus, the model was refined excluding the data of two mixes: 0.5% Hemp-30% coarse and 0.75% Hemp-10% coarse (Figure 2). The model was therefore improved as follows:

$$8641.3 + 0.495(E_{control})(1 - CR/100)(1 - V_f/100) + 0.837(AR)(V_f) \qquad (2)$$

where $E_{control}$: the modulus of elasticity test result of the control mix.

The predicted data fitted better around the 45° line, with the sum of the square of the error minimized to 9.39.



Mix	Measured	Predicte
0.5% Hemp - 10% coarse	18,935	19,194
0.5% Hemp - 20% coarse	17,304	18,024
0.5% Hemp - 30% coarse	21,543	NA
0.75% Hemp - 10% coarse	14,920	NA
0.75% Hemp - 20% coarse	20,679	18,011
0.75% Hemp - 30% coarse	16,134	16,844
1% Hemp - 10% coarse	18,966	19,162
1% Hemp - 20% coarse	16,960	17,998
1% Hemp - 30% coarse	17,088	16,834

Figure 2. Best Fitted Data for the Modulus of Elasticity Linear Model Incorporating CR, V_f, and AR (Measured Data from Awwad, 2012b).

Flexural Strength. Many trials were investigated for the beam flexure test maximum load linear model in order to optimize the predicted flexure peak load. The control mix average result used was 23.35 kN (Modulus of Rupture).

Table 3. Predicted Flexure Maximum Load Linear Model Trials.

$P_{predicted}$	E^2	Variables
$-249.46 + 10.70(P_{control})(1 - V_f/100)$	36.29	V_f only
$21.59 - 0.0013(P_{control})(AR)(V_f)$	37.15	AR & V_f
$19.16 + 0.061(P_{control})(1 - CR/100)$	37.95	CR only
$19.07 + 0.066(P_{control})(1 - CR/100)(1 - V_f/100)$	36.30	CR & V_f
$20.32 + 0.063(P_{control})(1 - CR/100)(1 - V_f/100) - 0.0316(AR)(V_f)$	36.99	CR, V_f, & AR
$8.61 + 0.510(P_{control})(1 - CR/100)(1 - V_f/100) + 0.0605(AR)(V_f)$	11.49	CR, V_f, & AR

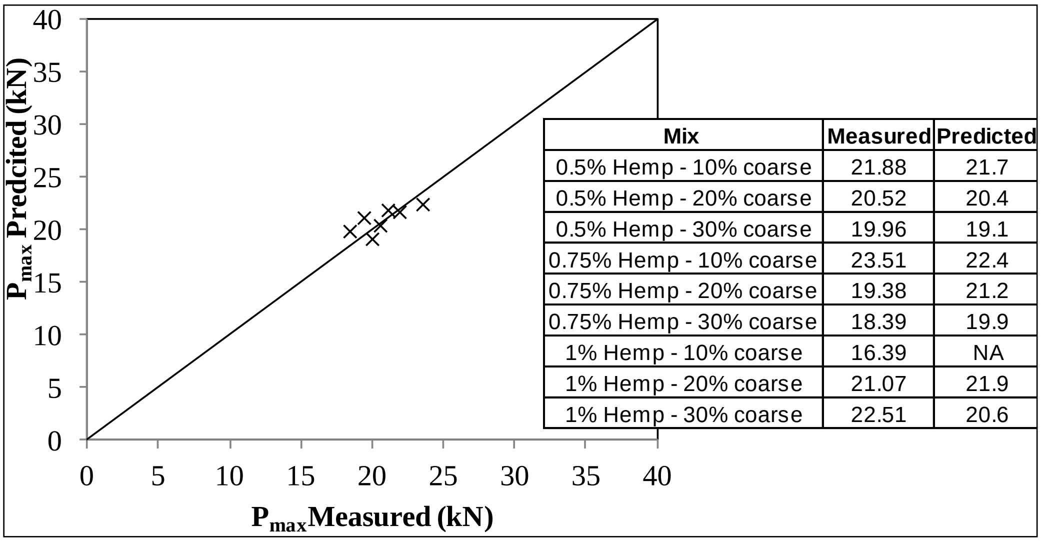
The sum of the square of the error (E^2) between the predicted ($P_{predicted}$) and measured peak load was calculated for all nine mixes and the minimum of the sum of the square of the error E^2 was targeted. It is worth noting that the orientation and distribution of fibers in every specimen may be different and the maximum load variation cannot be expected even for the same fiber-concrete mix. Besides, the stress plane in the flexure beam specimens is not linear and not one dimensional. Note that in the literature the prediction of flexure maximum loads is rarely considered, mostly the compressive strength and modulus of elasticity instead.

Referring to Table 3, when the volume fraction was only included, the model was not adequate and not sensitive to the volume fraction alone. The aspect ratio was added with the volume fraction in the model, and the model was still not adequate and not sensitive to both the volume fraction and aspect ratio. The coarse aggregate reduction was also investigated separately and the model was still not adequate. A combination of the coarse reduction and fibers volume fraction was investigated. Finally, the optimal linear model was found to be adequate when the coarse reduction, volume fraction, and aspect ratio were all included. The sum of the square of the error was minimized to 36.99 and the data were best fitted. The predicted data fitted around the 45^o line, but one outlier appeared to affect the model adequacy. Thus, the model was refined excluding the data of mix: 1% Hemp-10% coarse (Figure 3). The model was finally refined as follows:

$$8.61 + 0.510(P_{control})(1 - CR/100)(1 - V_f/100) + 0.0605(AR)(V_f) \tag{3}$$

where $P_{control}$: the flexure test result of the control mix.

The predicted data fitted well around the 45^o line, with the sum of the square of the error reduced to 11.49.



Mix	Measured	Predicted
0.5% Hemp - 10% coarse	21.88	21.7
0.5% Hemp - 20% coarse	20.52	20.4
0.5% Hemp - 30% coarse	19.96	19.1
0.75% Hemp - 10% coarse	23.51	22.4
0.75% Hemp - 20% coarse	19.38	21.2
0.75% Hemp - 30% coarse	18.39	19.9
1% Hemp - 10% coarse	16.39	NA
1% Hemp - 20% coarse	21.07	21.9
1% Hemp - 30% coarse	22.51	20.6

Figure 3. Best Fitted Data for the Flexure Maximum Load Linear Model Incorporating CR, V_f, and AR (Measured Data from Awwad, 2012b).

CONCLUSIONS AND RECOMMENDATIONS

Linear models were analyzed and investigated for the experimental tests results of the compressive strength, modulus of elasticity, and flexural strength. The linear models were shown to predict the hemp-fiber concrete mixes with acceptable ranges. Therefore, the availability of such analytical models would assist in predicting the behavior of hemp reinforced concrete mixes based on the control (plain) concrete mix, without the need to prepare and test hemp reinforced mixes. However, more sophisticated and nonlinear models may be needed as part of additional investigations to enhance the findings of the current research. Such models may be tested and validated by additional testing and recommended in future research work.

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REFERENCES

American Concrete Institute. A State-of-the-Art Report on Fiber-Reinforced Concrete, ACI Committee 544.1R-1996.

Al Rim K, Ledhem A, Douzane O, Dheilly RM, and Queneudec M. (1999). "Influence of the Proportion of Wood on the Thermal and Mechanical Performances of Clay-Cement-Wood Composites," Cement & Concrete Composites 1999; Volume 21, No. 4: pp. 269–276.

Awwad, E., Hamad, B., Mabsout, M., and Khatib, H. (2012a). "Sustainable Concrete using Hemp Fibers," Institution of Civil Engineers Journal - Construction Materials, DOI: 10.1680/coma.11.00006.

Awwad, E., Mabsout, M., Hamad, B., Farran, M., and Khatib, H. (2012b). "Studies on Fiber-Reinforced Concrete using Industrial Hemp Fibers," The Construction and Building Materials Journal, Elsevier, Vol. 35, October 2012, pp.710-717.

Awwad, E., Mabsout, M., Hamad, B., and Khatib, H. (2011). "Preliminary Studies on the Use of Natural Fibers in Sustainable Concrete," The Lebanese Association for the Advancement of Science Journal, Vol. 12, Issue No. 1, June 2011, pp.109-117.

Awwad, E., Hamad, B., Mabsout, M., and Khatib, H. (2010). "Sustainable Construction Material using Hemp Fibers – Preliminary Study," Proceedings of the Second International Conference on Sustainable Construction Materials and Technologies, Università Politecnica delle Marche, Ancona, Italy, June 28-30.

Awwad, E., Mabsout, M., Hamad, B., and Khatib, H., "Preliminary Studies on the Use of Natural Fibers in Sustainable Concrete," Proceedings of the 16th Science Meeting, Lebanese National Council for Scientific Research (LNCSR) and the Lebanese Association for the Advancement of Science (LAAS), Beirut Arab University, Lebanon, Nov. 13-15, 2009.

Barros J. A. O. and Figueiras J. A. (1999). "Flexural Behavior of SFRC: Testing and Modeling," Journal of Materials in Civil Engineering, Volume 11, No. 4, pp. 331–339.

Bilba K, Arsene MA, and Ouensanga A. (2007). "Study of Banana and Coconut Fibers Botanical Composition, Thermal Degradation and Textural Observations." Bioresource Technology 2007; Volume 98, No. 1: pp. 58–68.

Júnior L.Á.O., Borges V.E.S., Danin A.R., Machado D.V.R., Araújo D.L., El Debs M. K., and Rodrigues P.F. (2010). "Stress-Strain Curves for Steel Fiber-Reinforced Concrete in Compression." Revista Matéria Journal, Volume 15, No. 2, pp. 260–266.

Mansur M. A., Chin M. S., and Wee T. H. (1999). "Stress-Strain Relationship of High-Strength Fiber Concrete in Compression," Journal of Materials in Civil Engineering, Volume 11, No. 1, pp. 21–29.

Naaman, A., and Harajli, M. (1990). A State-of-the-Art Report on "Mechanical Properties of High Performance Fiber Concrete," University of Michigan, USA.

Savastano, H.Jr. Warden, P.G., and Coutts, R.S.P. (2005). "Microstructure and Mechanical Properties of Waste Fibre Cement Composites," Cement & Concrete Composites 27, pp. 583–592.

Zhu, W.H., and Tobias, B.C. (1994). "Air-Cured Banana Fibre Reinforced Cement Composites," Cement and Concrete Composites 1994; Volume 16, No. 1: pp. 3–8.