A Novel Evaluation Tool for Enhancing the Selection of Natural Fibers for Polymeric Composites Based on Fiber Moisture Content Criterion

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A systematic evaluation tool for natural fibers' capabilities based on moisture content criterion (MCC) was developed and introduced as a new evaluation method. This MCC evaluation tool is designed to predict the behavior of the available natural fibers regarding distinctive desirable characteristics under the effect of the moisture absorption phenomenon. Here, the capabilities of different natural fiber types commonly used in industry, in addition to date palm fibers, were systematically investigated based on MCC. The results demonstrated that MCC is capable of predicting the relative reduction of fiber performance regarding a particular beneficial property because of the effect of moisture absorption. The strong agreements between the predicted values of MCC and results reported in the literature verify its usefulness as an evaluation tool and demonstrate its added value steps in predicting the relative behavior of fibers with a minimal range of errors compared with experimental measurements. Therefore, MCC is capable of better evaluating natural fibers regarding distinctive criteria in a systematic manner, leading to more realistic decisions about their capabilities and therefore enhancing the selection process for both better sustainable design possibilities and industrial product development.

Keywords: Natural fibers; Moisture content; Polymeric composites; Sustainable design; Evaluation tool; Date palm fibers

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INTRODUCTION

Proper material selection has become crucial in engineering to achieve a competent, sustainable design with higher customer satisfaction attributes. The implementation of new materials, as well as bio-composites, in a specific industrial sector is limited by several constraints and factors (AL-Oqla and Sapuan 2014). Therefore, selecting the most suitable type of material for a particular application is a complex matter in which proper evaluations and decisions have to be made utilizing informative pairwise comparisons, which is the core of the decision-making process in different engineering applications (AL-Oqla and Hayajneh 2007; Al-Widyan and AL-Oqla 2011; 2014; AL-Oqla and Omar 2012, 2014; AL-Oqla *et al.* 2014). The present tremendous need for achieving both sustainability and better environmental performance reveals the eligibility of the available natural fibers and their composites for various industrial applications. Natural fiber composites (NFCs) have recently been emphasized as potential eco-friendly, cheap alternatives to traditional composites because of their desirable features, including low cost, light weight, high specific properties, ease of manufacturing, recyclability, and degradability characteristics (Pilla 2011; AL-Oqla and Sapuan 2014). A wide variety of natural fiber types had been used to reinforce various polymer matrices as a substantial raw material source for renewable products. They are generally classified based upon their origin as bast fibers, leaf fibers, fruit, and seed-hair fibers. The available natural fibers include cotton, flax, wood, pineapple leaf, curaua, bagasse, rice straw, rice husk, wheat straw, hemp, coir, kenaf, oil palm, ramie, date palm, jowar, bamboo, rapeseed waste, doum fruit sisal, and jute (Jawaid and Abdul Khalil 2011; Majeed *et al.* 2013).

Although several investigations regarding NFCs' competitiveness and capabilities as eco-friendly alternative materials have been conducted (Alawar *et al.* 2009; Abdal-hay *et al.* 2012; Mir *et al.* 2013; Sapuan *et al.* 2013; AL-Oqla *et al.* 2014), very few studies were found investigating the evaluation and selection of natural fiber composites' constituents. Recently, added value steps in establishing evaluation tools for natural fibers and their composites have been performed to help designers in selecting and evaluating such materials for sustainable green products. Such steps included categorization frameworks for the factors that affect NFCs (AL-Oqla and Sapuan 2014), and a combined evaluation scheme for better evaluating the capabilities of the available natural fibers regarding simultaneous combined evaluation criteria (AL-Oqla *et al.* 2014).

Moisture Absorption and Natural Fibers' Capabilities

The totality of NFCs' attributes and capabilities depend on the physical and chemical composition of their inherent constituent materials. Therefore, NFC materials should be investigated regarding various features and properties before being considered for any particular application.

During their lifetimes, NFCs are often submitted to variable conditions, including high humidities and exposure to liquid water. The hydrophilic behavior of natural fibers leads to high levels of moisture absorption in wet conditions, which causes a pronounced influence on their mechanical performance. The hygroscopic characteristic of the agro-waste natural fiber is critical for its overall mechanical applications, as it dramatically reduces bonding between the matrix and filler in NFCs and thus decreases their desired mechanical performance (Azwa *et al.* 2013; Sapuan *et al.* 2013). Thus, the high moisture absorption of natural fibers is one of their most undesirable characteristics as it causes several catastrophic effects in the composites, such as swelling, loss of mechanical properties, acceleration of fiber degradation, cracking, and inviting decay fungi (Azwa *et al.* 2013; Sapuan *et al.* 2013). The hemicellulose and moisture contents of a natural fiber are the main factors responsible for its level of moisture absorption, thermal and biological degradation, and flammability (Azwa *et al.* 2013). Therefore, the chemical composition of natural fibers is of paramount importance for most industrial applications, as it is important for their chemical, mechanical, degradable, and biological characteristics.

Although the influence of moisture absorption on the mechanical performance of natural fibers has been investigated in the natural fiber composite field, results reported in the literature are not altogether consistent (Célino *et al.* 2014). It has been reported that the moisture absorption level may enhance or worsen composite properties, depending on the fiber and matrix types (Azwa *et al.* 2013). It has also been reported that water absorption may enhance a particular mechanical property for certain fiber types, whereas it may reduce it for others (Symington *et al.* 2009; Placet *et al.* 2012; Azwa *et al.* 2013). However, the distinctive behavior of different fiber types regarding the effect of moisture is not yet well-understood. This makes it difficult to predict the relative performance of fibers under wet conditions during their lifespans. Also, inconsistencies in the reported results regarding this effect make the selection of an appropriate natural fiber type to form an NFC for unsteady conditions a sophisticated process.

Addressed Gap and Work Objectives

Based on the literature, an obvious lack of information regarding the proper evaluation and selection of natural fiber composites constituents (fillers and matrices) was observed. More precisely, evaluating the available agro-waste fibers for polymeric-based composites is not often enough discussed in terms of the distinctive desired criteria (AL-Oqla *et al.* 2014; AL-Oqla and Sapuan 2014). Therefore, further systematic investigations and extensive comparisons between NFCs' constituents are needed in order to better evaluate and control these types of bio-based composites.

On the other hand, inconsistency in the literature was found regarding the effect of water absorption on the mechanical performance of natural fibers (Célino *et al.* 2014), with high levels of standard deviations. This may be caused not only by the inherent variation in quality within the same fiber type, but also by the cumulative errors in the performed measurements during the determination of a particular fiber property (Symington *et al.* 2009). Furthermore, there was no previous systematic method for predicting the relative performance of fibers under the effect of water absorption, and thus, there was no impervious systematic process for evaluating the available natural fibers under wet conditions during their lifetimes.

Consequently, the aim of this work was to design and present an evaluation tool capable of predicting the relative performance of the available natural fibers in terms of their desired distinctive characteristics under the effect of the moisture absorption phenomenon. This can help designers to properly evaluate and select the most appropriate natural fiber types to expand their sustainable design possibilities, as well as contribute to the selection process of natural fibers and their composites. More precisely, a systematic evaluation tool for natural fibers' capabilities based on moisture content criterion (MCC) was developed and introduced as a new evaluation scheme. In addition, toward introducing new potential natural fiber types capable of supporting and expanding sustainable design possibilities, the capabilities of date palm fibers were revealed and compared with more commonly used fibers in terms of various desired characteristics with and without MCC to contribute to the industrial sustainability theme.

EXPERIMENTAL

Methods

To enhance better selection of natural fibers, the relative capabilities of commonly used fiber types in addition to the date palm one are illustrated based on the fiber moisture content criterion (MCC, Fig. 1). To illustrate the effectiveness of the proposed evaluation criterion, various pairwise comparisons of different fiber types with and without MCC were conducted.

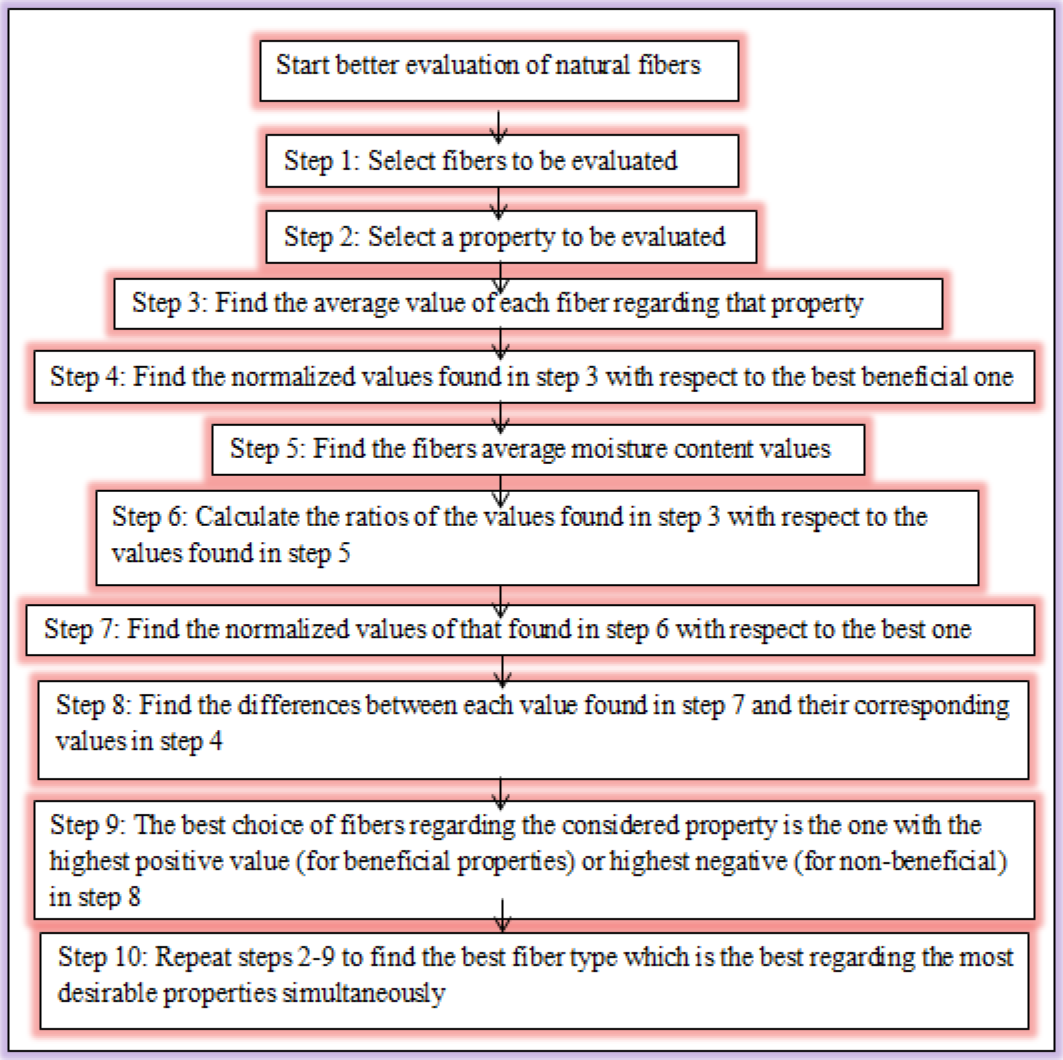

Fig. 1. Flow chart of the proposed MCC evaluation tool

In this proposed MCC, the performance of each fiber has to be found relative to all compared fibers as normalized values, and then each fiber's performance has to be found relative to its moisture content. After that, new normalized values (relative performance) based on values found relative to each fiber's moisture content have also to be found. The relative performances of the fibers characteristics before and after MCC are normalized with respect to the best beneficial values. After that, the changes in performance (positive or negative) between the normalized values are calculated. These variations are used to indicate the capability of a certain fiber type regarding a particular characteristic. The fiber type with more positive increments in performance (for beneficial properties) or more negative (for non-beneficial) after using the MCC is recommended for further ecofriendly sustainable design. The fiber with high negative values (reduction in performance) before and after the MCC is not further recommended for industrial applications due to its relative deterioration in performance compared to other fibers. That is, the fiber with negative deviation in the normalized performance regarding a particular beneficial property indicates a negative influence in performance (performance deterioration) due to water absorption compared to other fibers. Such performance deterioration is supposed to be due to the fibers' inherent moisture content that encourages fungal decay, swelling, aging, and incompatibility with the matrix, as well as general mechanical instabilities. Then comparing fibers to each other, the one with the highest positive deviation in the normalized value is judged to be the best regarding that particular property, and the best choice of fibers that can support further design possibilities is the one with the highest number of positive increments in various characteristics after applying the MCC. Moreover, to give more clarification of the proposed method, each comparison with respect to each selected characteristic was conducted and interpreted in a separate figure. Such comparisons regarding various evaluation criteria can be the key driver to enhance both the selection process and development of the NFCs products for a given industrial application. The flow chart of the proposed methodology is illustrated in Fig. 1.

RESULTS AND DISCUSSION

Investigations without MCC

Evaluating the capabilities of natural fibers in the design stage based on moisture content criterion can help with the prediction and capture of the relative performance deterioration of natural fibers caused by the water absorption phenomenon. This can also help to obtain better information about the capabilities of fibers in order to enhance the selection of the most appropriate fiber type for a particular design. The moisture content of natural fibers varies according to their chemical compositions. The moisture content of the date palm fiber is considered competitive compared with others (within the range of 5 to 12.5% of its weight from dry to wet conditions). The different properties of some fiber types commonly used in industrial applications, in addition to the date palm, are listed in Table 1 (Dittenber and GangaRao 2011; Pilla 2011; AL-Oqla *et al.* 2014; AL-Oqla and Sapuan 2014).

Table 1. Properties of Natural Fiber Composites

Fiber type	Coir	Date palm	Flax	Hemp	Jute	Sisal
Density (g/cm^3)	1.15-1.46	0.90-1.20	1.40-1.50	1.40-1.50	1.30-1.49	1.33-1.50
Tensile strength (MPa)	95-230	97-275	343-2000	270-900	320-800	363-700
Tensile modulus (GPa)	2.8-6.0	2.5-12.0	27.6-103.0	23.5-90.0	8.0-78.0	9.0-38.0
Elongation to break (%)	15.0-51.4	2.0-19.0	1.2-3.3	1.0-3.5	1.0-1.8	2.0-7.0
Moisture content (wt %)	8.0	5.0-12.1	8.0-12.0	6.2-12.0	12.5-13.7	10.0-22.0

Comparisons between different natural fiber types, including coir, date palm, flax, jute, hemp, and sisal were conducted regarding some beneficial characteristics to demonstrate the effectiveness of the developed MCC evaluation tool and illustrate the competitiveness of date palm fibers for sustainable design considerations compared with other fiber types. Because of the tendency of natural fibers to show wide variations in their properties according to their qualities, the average values in all comparisons were used, which is considered reasonable for comparison purposes in the natural fiber field

(Rowell *et al.* 1997; AL-Oqla *et al*. 2014; AL-Oqla and Sapuan 2014). A comparison regarding the average values of fiber moisture contents is shown in Fig. 2. It is obvious that natural fibers vary in their moisture contents, which affects their long-term performance under wet conditions. Only coir fiber has lower moisture content than date palm. This naturally helps date palm to resist fungi, swelling, and moisture absorption better than hemp, flax, jute, and sisal. It can also be seen that the moisture content of date palm is about one half that of sisal, and only two thirds that of jute. Thus, it can be deduced that date palm fiber can perform more efficiently than other fiber types under the effect of moisture absorption under the same conditions, *i.e.*, the effect of moisture absorption on date palm performance will be much lower than that of sisal and jute, which is illustrated in the following combined evaluations using the proposed MCC.

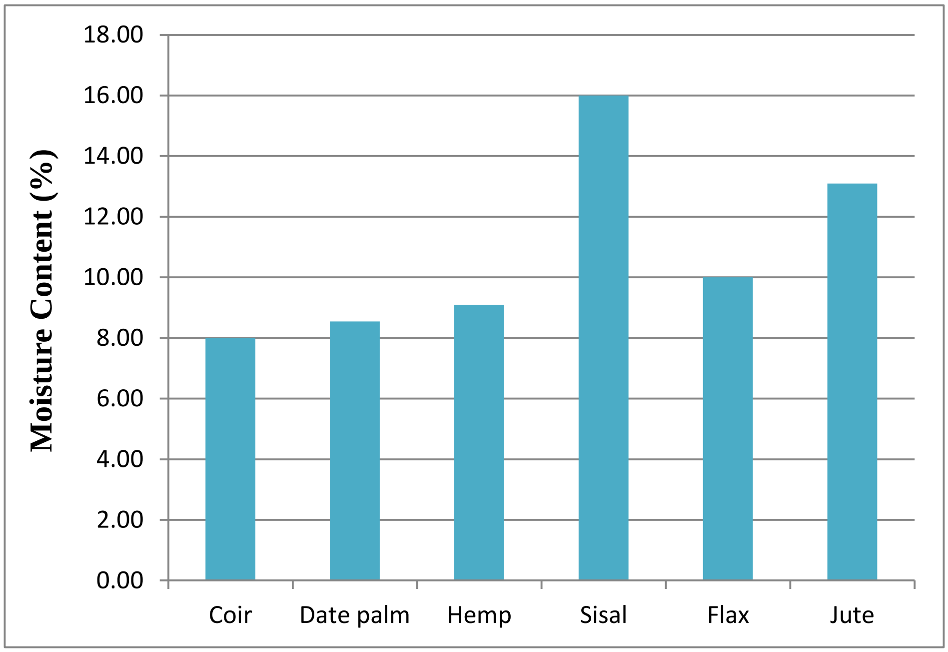

Fig. 2. Average values of moisture contents for various fibers

Another comparative investigation regarding the elongation to break property is illustrated in Fig. 3. This property is considered necessary for natural fiber products as it is beneficial for resisting impact loading. The competitiveness of date palm fiber is also obvious as it has higher elongation to break values than hemp, sisal, flax, and jute. It is clear that date palm possesses more than a double value of this beneficial property compared with sisal, and significantly more than that compared with hemp, flax, and jute.

Investigations Utilizing MCC

Although comparisons of natural fibers regarding various mechanical properties such as elongation to break can give information regarding their capabilities, combined evaluations can give more realistic ones. However, before utilizing such values to draw conclusions regarding the selection of the most appropriate natural fiber type for an engineering design, particularly for wet conditions, the important question of how these fibers will behave under conditions where the water absorption phenomenon can occur must be answered to increase the reliability of implementing such fibers for green products and predicting their future performance under water absorption effects.

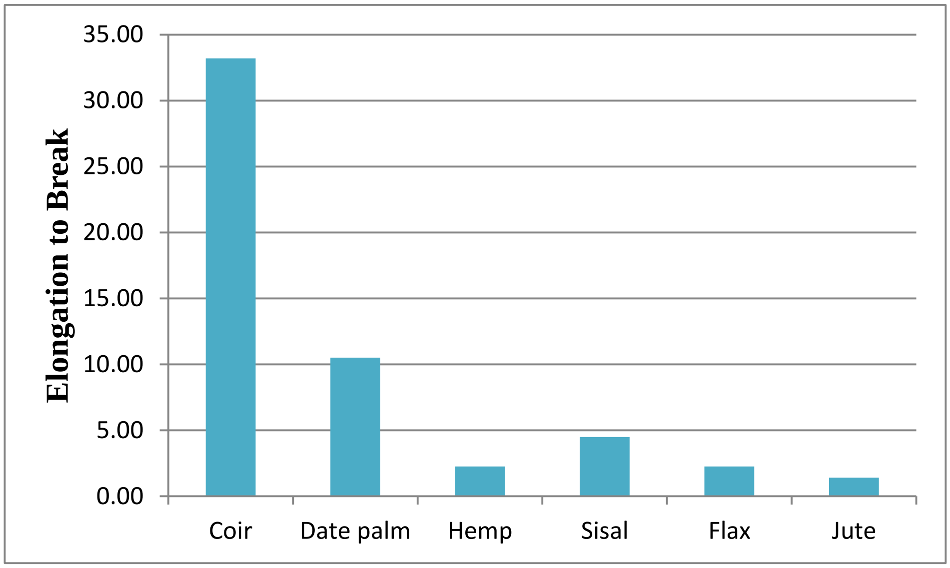

Fig. 3. Elongation to break of various fibers

In other words, one can ask whether the relative performance of these fibers would be the same under the effect of water absorption after their implementation in products. Although a series of lengthy experimental work may answer such a question, the introduced MCC evaluation tool can predict such an answer in a simple, systematic way (Fig. 1) to help designers better evaluate and select the most suitable type of material for their sustainable designs.

To predict the relative performance of such fibers regarding a beneficial property, such as elongation to break, the considered values of elongation to break must be normalized according to the best value (33.2 for coir), as seen in Table 2, which contains detailed calculations for this property. Then, the fibers' elongation to break values must be found relative to their moisture contents as elongation to break/moisture content (EL/MC), and then normalized according to the best ratio of the compared fibers, which is 4.15 for coir. After that, the differences between the normalized values (NOR EB/MC)-(NOR EB) are calculated, as seen in Table 2. This can capture the relative performance of natural fibers after applying MCC and their original relative performance for a certain property. These differences for elongation to break are illustrated in Fig. 4.

These values can predict whether performance deterioration for a certain fiber type will occur relative to the best compared performance. In this case, all fiber types will have similar performance deterioration regarding elongation to break relative to coir performance, but with different values. That is, the best fiber regarding elongation to break is coir followed by hemp, as its performance will be least affected under the effect of moisture absorption as it has a low performance in elongation to break relative to low moisture content value. Besides, the performance of sisal fiber was dramatically affected by the moisture absorption phenomenon and considered to have the poorest elongation to break property. However, this was not obvious before applying MCC, as sisal was not the worst before applying MCC (Fig. 3).

It can be deduced from MCC that although some fibers (like sisal) have relatively good performance in a particular property such as elongation to break (sisal has better performance in elongation to break than hemp, flax, and jute), they might not be considered an appropriate choice after MCC, as their performance will be negatively influenced and their moisture contents will cause significant deterioration in their performance. Moreover, the performance of some fibers such as flax and jute are expected not to be dramatically affected by moisture absorption. This is in contrast to date palm, whose high values and good performance in terms of elongation to break may be more affected by moisture absorption than flax and jute, as they have poor original performance regarding elongation to break (Fig. 3).

Table 2. Detailed Calculations for Predicting the Relative Performance of Fibers Regarding the Elongation to Break Property with the MCC Evaluation Tool

	Coir	Date palm	Hemp	Sisal	Flax	Jute
Moisture content (MC) (%)	8.000	8.550	9.100	16.000	10.000	13.100
Elongation to break (EB) (%)	33.200	10.500	2.250	4.500	2.250	1.400
Normalized EB (NOR EB)	1.000	0.316	0.068	0.136	0.068	0.042
EB/MC	4.150	1.228	0.247	0.281	0.225	0.107
Normalized EB/MC (NOR EB/MC)	1.000	0.296	0.060	0.068	0.054	0.026
NOR(EB/MC)-NOR(EB)	0.000	−0.020	−0.008	−0.068	−0.014	−0.016

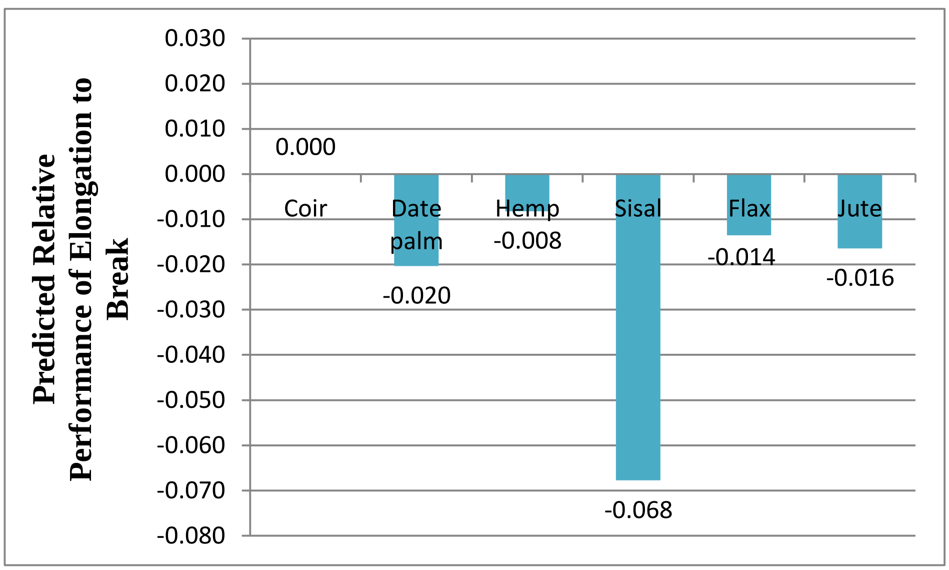

Fig. 4. Predicted relative performance reduction regarding the elongation to break property compared with coir fiber using MCC

Further comparative investigations and evaluations of natural fibers can be performed in a similar manner. Predicting the relative performance of fibers under the moisture absorption effect regarding tensile strength was conducted and interpreted in Fig. 5:

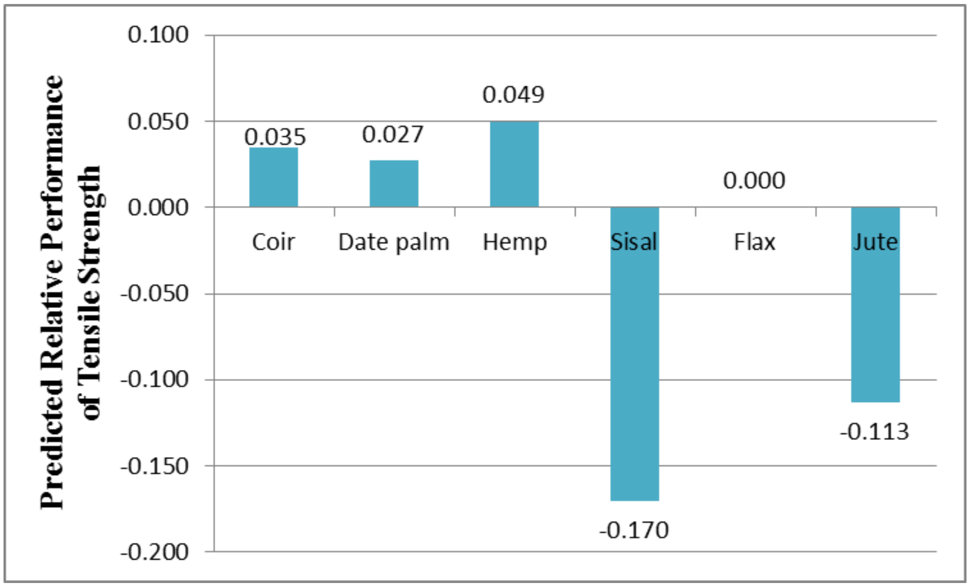

Fig. 5. Predicted relative performance of tensile strength relative to flax fiber utilizing MCC

Results in this particular investigation predict (utilizing MCC) that sisal will show a reduction in performance (in soaked condition relative to the regular one) regarding the tensile property by more than 15%. Jute is also predicted to have a reduction in its performance of more than 10%, whereas coir, date palm, and hemp are predicted to exhibit improvement in their behaviors regarding this property under the effect of water absorption. The maximum improvement will be for hemp, with about a 5% increase. This predicted improvement in the performance regarding tensile property is considered an added-value step of the proposed MCC, as similar improvements in natural fiber composite behaviors after water absorption have been achieved and reported in various works (Dhakal *et al.* 2007; Alamri and Low 2012; Azwa *et al.* 2013; Sapuan *et al.* 2013; Abral *et al.* 2014; Kuciel *et al.* 2014).

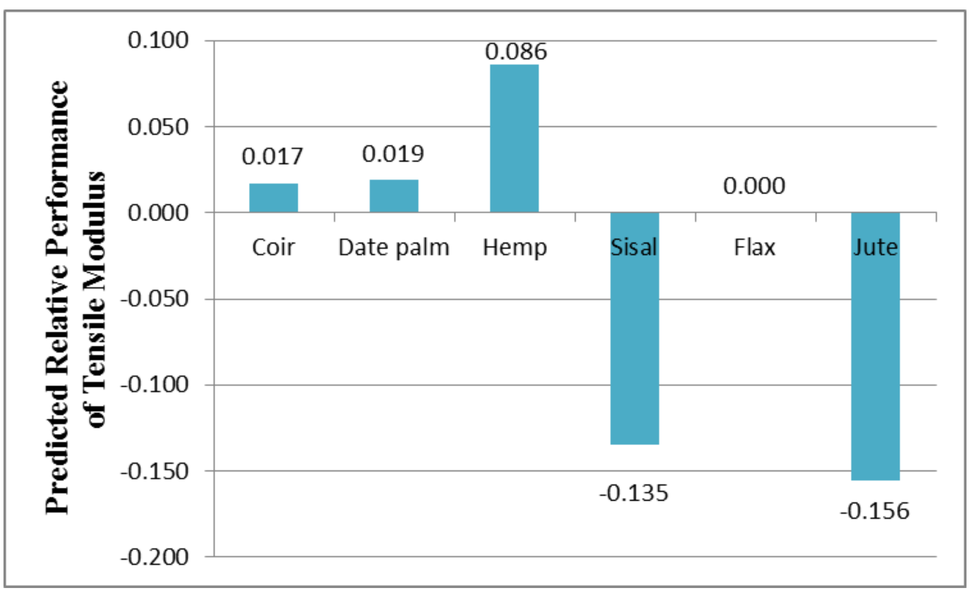

Fig. 6. Predicted relative performance of tensile modulus utilizing MCC

Similarly, the predicted behavior of fibers regarding tensile modulus after applying the MCC evaluation tool shows that coir, date palm, and hemp will all have improved behaviors under water absorption, with a maximum of 8.6% for hemp, whereas both sisal and jute will be negatively affected, as seen in Fig. 6. Particularly, it is predicted that sisal will have about a 13.5% reduction in tensile modulus, and jute will have a 15.6% reduction, meaning it will display the worst performance compared with other fibers.

Results Agreements

Although the proposed MCC evaluation tool is presented to compare the performance of different natural fibers under water absorption, the verification of the gained results for all considered fiber types as well as others is difficult to perform and requires much effort and time. However, various agreements and synchronization with our predicted results were found in the literature as an indication of the MCC evaluation tool's validity. For instance, Symington *et al.* (2009) studied the effect of water absorption and humidity on the tensile properties of various cellulose-based fibers. In that work, tensile strength, tensile strain to failure (%), and Young's modulus were tested in dry conditions as well as under different humidity conditions, including soaked cases. In each case, an average value of 25 tests for each fiber type was considered because of the potential variability in natural fiber properties. However, high standard deviations were noticeable for many of the fibers from the same batch in different tests. The soaking condition cases from that work were used here as strong verifications for the validity of our proposed MCC evaluation tool. Their measured values for the elongation to break property of coir, jute, flax, and sisal fibers before water absorption (dry) and after (soaked) are shown in Table 3.

Table 3. Effect of Water Absorption on Elongation to Break of Different Fibers (Symington *et al.* 2009)

<table>
<tr><th colspan="7">Elongation to Break (%)</th></tr>
<tr><th>Fiber</th><th>Dry</th><th>Water-soaked</th><th>Performance</th><th>Performance (%)</th><th colspan="2">Notes</th></tr>
<tr><td>Sisal</td><td>2.9</td><td>2.0</td><td>−0.9</td><td>−31.0%</td><td>Reduction occurred as expected</td><td rowspan="4">The worst reduction occurred in sisal (31%), then in jute with 26.3%, and finally in flax with 24%. This was in concurrence with the MCC, which predicted that sisal would be the worst, followed by jute and flax.</td></tr>
<tr><td>jute</td><td>1.9</td><td>1.4</td><td>−0.5</td><td>−26.3%</td><td>Reduction occurred as expected</td></tr>
<tr><td>flax</td><td>2.5</td><td>1.9</td><td>−0.6</td><td>−24.0%</td><td>Reduction occurred as expected</td></tr>
<tr><td>coir</td><td>19.0</td><td>22.5</td><td>3.5</td><td>+18.4%</td><td>Improvement occurred as it is the best in elongation to break</td></tr>
</table>

It can be seen from Table 3 that a reduction in elongation to break performance for sisal, jute, and flax was achieved compared with coir fibers, which was also expected according to the MCC evaluation tool. However, coir fiber retained the highest elongation to break performance, as predicted by MCC. Furthermore, deeper investigations of Table 3 reveal that the maximum reduction in performance caused by the water absorption effect was found in sisal (31.0%), followed by jute and flax, exactly as predicted by the MCC evaluation tool (Fig. 4). This agreement demonstrates the effectiveness of MCC as a novel evaluation tool for the relative performance of natural fibers relative to the water absorption effect. Thus, MCC can be utilized for the proper evaluation and selection of natural fibers for polymeric composites in different industrial applications.

On the other hand, the accuracy in measuring the effect of moisture absorption on tensile strength was reported by the same authors (Symington *et al.* 2009) as a less accurate test compared with that performed for elongation to break and tensile modulus. That was because of high standard deviation values (even higher than those reported in the literature). This can add value to the proposed MCC evaluation tool as it can predict the relative performance of fibers in a systematic manner with less cumulative errors and more reliable results. That is, MCC is based on a relative performance scheme with less lab work and thus less measurement errors.

Moreover, strong agreements and verifications of the predicted MCC values were also found regarding the effect of moisture absorption on the tensile modulus of fibers. It was reported by Symington *et al.* (2009) that the measured tensile modulus for sisal fiber after water absorption was 17 GPa, whereas for dry fibers, it was 17.8 GPa (4.5% performance reduction). The tensile modulus of jute fiber after water absorption was also found to be 23.6 GPa, compared with 28 GPa for the dry fibers, (about 15.7% reduction). However, a 40% improvement in the coir's tensile modulus performance was achieved; its tensile modulus after water absorption was found to be 4.5 GPa, compared with 3.2 GPa in the dry fibers. These trends in the improvement of coir fiber performance, as well as the performance reduction of both sisal and jute regarding tensile modulus, were obviously predicted in the MCC evaluation tool. More precisely, the MCC was able to predict that the performance reduction for jute would be higher than that of sisal, and the performance of coir would not be reduced because of water absorption for this particular criterion, but, on the contrary, it would be improved (Fig. 6).

More and more agreements with predicted MCC results have been found in different works, even regarding the composite level. For instance, Costa and d'Almeida (1999) studied and compared the mechanical properties of both sisal and jute composites under the effect of water absorption (with different fiber size, random orientations, matrix treatments and catalysts). They reported that after a long duration (7500 h) of immersion the polyester-based composites in distilled water (with the same fiber loading), the ultimate tensile strength of the jute-polyester composites was reduced from 43 MPa to 30.4 MPa (29.3% reduction), whereas the ultimate tensile strength of sisal-polyester composite was reduced from 34.6 MPa to 18.8 MPa (45.6% performance reduction). This means that the reduction in tensile performance of sisal composite was about 1.55 times that of jute composite, which is exactly the predicted value from MCC as seen in Fig. (5), where a ratio of 1.50 as (0.170/0.113) was predicted. This can demonstrate the effectiveness of our proposed MCC evaluation tool.

The same authors (Costa and d'Almeida 1999) compared jute and sisal fibers with epoxy matrix, where a performance reduction in elastic modulus was found to be about 1.18 times for jute, while the MCC predicted it to be about 1.15 for sisal. This slight change in values is caused by the fact that both the predicted and experimental relative ratios are very close to the value of one. This indicates the validity of the MCC; however, the reported variations (standard deviations) of measured values in the experimental work explain why the results slightly differed from the predicted value. This also can be considered as being an added-value step of the MCC, where clearer indication of fiber performance can be achieved by eliminating the cumulative errors that may change fiber preferences in the evaluation and selection processes.

All such agreements of the predicted behaviors of fibers between the introduced MCC evaluation tool and measured values in the literature are not only considered verification of the validity of the MCC evaluation tool, but also reveal the importance and novelty of the MCC, as well as its added value-step in predicting the relative performance of fibers and determining the stability of fibers when exposed to various environmental conditions.

CONCLUSIONS

1. The moisture content of natural fibers can be utilized to predict their behaviors under water absorption.
2. The introduced Moisture Content Criterion (MCC) evaluation tool was capable of predicting the relative deterioration and/or improvement of various natural fibers' behavior under the water aging effect.
3. The effectiveness of the proposed MCC was successfully demonstrated by its evaluation of different natural fiber types, where strong agreements with the predicted values were found in the literature.
4. Moisture Content Criterion is an added-value step because it can predict the performance of natural fibers under the water absorption effect systematically and without cumulative errors comparable with the measurement procedures in the experimental work.
5. Moisture Content Criterion as a new evaluation tool was capable of better evaluating different natural fibers and enhancing their selection process for the condition of wet environments.
6. Date palm fiber was found to be competitive for applications under wet conditions as its performance was not negatively affected by water absorption relative to other types of fiber.

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