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Wood-cement composites using suitable mix of sawdust and fibres from veins of palm tree leaves

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Some tropical wood species are currently used in wood work and generating an important quantity of wood waste in Benin, Western Africa. Recycling these wastes through building material is a way to solve environmental challenges, but the wood resources are not inexhaustible and vegetable fibers such as *Eleais guineensis* fibers, obtained from veins of palm tree leaves are available in nature. The main concern of this study is to determine the most suitable mixes of *E. guineensis* fibers and five West African hardwood species namely *Diospyros mespiliformis, Khaya grandifoliola, Tectona grandis, Pterocarpus erinaceus and Isoberlina doka* for wood-cement composites. The compatibility with cement of mixes of fibers and sawdust is studied based on measurements of cement heat hydration and compatibility indices. The tensile and compressive strengths of the composites were determined to evaluate the potential of the mixes. The results show that the woody residues inhibit the hydration reactions of cement and greatly more when containing *E. guineensis* fibers. Hydration tests indicated that all the mixes could be rated as having moderate to good compatibility with cement after hot water treatment. Mechanical tests showed that the mixes containing *Isoberlina doka, Tectona grandis* and *Khaya grandifoliola* sawdust provided the highest mechanical strengths.

Key words: Vegetable fibers, sawdust, compatibility, wood-cement composites, mechanical strengths.

INTRODUCTION

In Benin, a West African country, the forest cover is about 68% of the total superficies of 114 763 km², according to a recent World Bank report (2010). The per capita income according to the same report is 690 USD. Overall wealth of this country has an important component that is derived from forest resources. Many tropical species are identified to be hard wood and generate significant volumes of wood commercially viable. Consequently, large quantity of wood waste is generated in this region and will constitute a considerable environmental problem. In most of the West African countries, a very moderate fraction of wood waste is used to provide energy for

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domestic use while a great proportion of such waste is consumed in the nature releasing carbon dioxide and other gas in the environment.

The re-use of wood waste as building materials is one of the few ways of tackling the problem. But the wood resources are not inexhaustible and it would be suitable to use the mixes of sawdust and vegetable fibers such as those from palm oil veins, available in the nature for wood - cement composites. Ordinary wood-cement composites obtained by mixing sawdust, water and cement have been widely investigated (Dinwoodie and Paxton, 1984; Hachmi and Sesbou, 1990; Hofstrand et al., 1984). The dimensional variations have been studied by Mougel (1992). The major well known problem occurring with regards to this topic is the aptitude of wood species to be used as wood - cement composites. Such a problem is widely discussed recently (Pereira et al., 2003, 2004). Many studies have been undertaken to assess the compatibility of wood with cement (Hachmi and Moslemi, 1989; Hachmi et al., 1990; Sandermann and Kolher, 1964).

To build houses with walls made from wood cement-composite is a way not only to solve environmental problem but to provide many other advantages. It is a very lightweight material which allows saving of money as reported in the thesis of Doko (2013). It is also a material which provides heat insulation.

Today, although a large number of wood species have been investigated such as pin wood (Semple and Evans 2000), Western Australian *malle Eucalyptus* (Semple et al., 2002), *Acacia mangium and Eucalyptus pellita* (Semple et al. 1999), *Amblygonocarpus andongensis, Brachystegia speciformis, Pterocarpus angolensis, Kaya nyasica, Erythrophleum suaveoleuns, Albizia adianthifolia, Sterculia appendiculata, Millettia stuhlmannii, Julbernadia globiflora and Afzelia quanzenzis* (Alberto et al. 2000), few information related to the compatibility of wood species with cement is available. That is the same thing with the mixes containing various tropical fibers. Moreover, it was widely discussed (Alberto et al., 2000) that the nature of wood species considerably influences the hardening of the cement depending on the origin of the tree. Evaluating some physical properties for oil palm stem as alternative biomass resources, Balkis et al. (2012) concluded that the middle and center sections of oil palm stem contained the highest amount of extractives using hot water extraction. The lowest amount of extractives was located at the bottom outer section of the oil palm stem.

Although today, researchers reveal more and more new environmental problems generated by manufacturing wood cement composite; we must keep in mind that the transformation process of the wood residues should avoid the creation of other environmental problems. Indeed, Silva et al. (2013) reported that in Brazil, the wood panel industry is one of the most important forest-based industries. Assessing the life cycle of medium density particleboard (MDP), they found that unlike other regions, Brazilian MDP is produced from dedicated eucalyptus plantations and heavy fuel oil is an important energy source in MDP manufacture with a negative impact on the environment. They suggest the possibility of using alternative production MDP scenarios as substituting heavy fuel oil (HFO) for in-mill wood residues or diesel or finding other sources of wood for MDP production.

The aim of this research initiated in Benin was to determine the most suitable mixes of *Eleais guineensis* fibers and five West African hardwood species for wood-cement composites. The first step in assessing the suitability of different mixes containing wood species and vegetable fibers for cement composites involves testing whether the mix significantly inhibits the hydration reaction of Portland cement. Compatibility with cement of mixes of *E. guineensis* fibers and five wood species based on the measurement of cement hydration temperature and compatibility indices was studied. In the second step, mechanical tests were carried out on moulded blocks to confirm hydration tests as indicated by Andy and Land Zhongli (1986). In the third step, the suitability of mixes for wood-cement composites were evaluated by carrying out tensile and compressive tests on the samples made from mixes of vegetable fibers and sawdust.

MATERIALS AND METHODS

Sawdust taken from sawmills for five wood species available in Benin (Figure 1a) were used in this study: *Diospyros mespiliformis, Khaya grandifoliola, Tectona grandis, Pterocarpus erinaceus* and *Isoberlina doka*. *Eleais guineensis* fibers (Figure 1b) are vegetable fibers obtained from ground oil palm veins previously dried.

In order to assess the influence on the compatibility indices of the treatment method applied, the mixes (*E. guineensis* fibers and wood sawdust) were pre-treated firstly with cold water and secondly with hot water. Treatment in cold water consisted of drenching during 48 h and washing thoroughly sawdust and fibers in water at ambient temperature. Treatment in hot water consisted of drenching for 48 h and washing sawdust and fibers in water at 80°C because of their great degree of inhibition assumed (Badejo, 1989; Hachmi and Moslemi, 1989; Pereira et al., 2003).

After washing, both the sawdust and *E. guineensis* fibers were dried in a kiln at 105°C within 48 h then separated by sieving in three size classes. Class retained for the tests was 0, 1 - 4 mm. The type of cement used was CPJ-CEMII 35 manufactured in SCB Lafarge Company and locally available in Benin.

Measurement of cement hydration temperature and compatibility indices

The mass ratios used were: Sawdust/*E. guineensis* fibers/cement/water mass ratio of 12:3:200:90.5 g inspired from the work of Weatherwax and Tarkow (1964) in which wood/cement/water mass ratio was 15:200:90.5 g. In this study, the wood is considered as the mix of sawdust (12 g) and *E. guineensis* fibers (3 g). The lower proportion of vegetable fibers in wood (1:5) has been adopted because of its probable great degree of inhibition presumed.

Figure 1. Sawdust (a) and fibres from veins of palm oil leaves (b).

Table 1. Most convenient ratios for wood species.

Wood species in the mixes of sawdust and *Eleais guineensis* fibers	Water/cement/ ratio in weight
Diospyros mespiliformis	00.85
Khaya grandifoliola	0.87
Tectona grandis	0.61
Pterocarpus erinaceus	0.84
Isoberlina doka	1.09

Cement control sample: 200 g of cement mixed with 80 ml of water was used (Weatherwax and Tarkow, 1964).

The samples were thoroughly mixed with water in a sealable polyethylene bag for 2 min. Immediately after mixing, the tip of a temperature thermocouple (type K) was taped to the outside of sample bag and enclosed within the body of the wood-cement mix by folding the bag and contents around it and securing the folded bag with adhesive tape. The bag was then placed in a polystyrene cup and sealed inside a flask. This process was carried out for three samples per test. All experiments were undertaken in a controlled temperature room maintained at 20 ± 1°C. A cement hydration temperature logging apparatus was used to measure the heat of hydration of the three wood-cement samples for 24 h. Temperatures were recorded at 5 min intervals and the curves were smoothed by plotting the progressive averages of every three successive readings. Maximum heat of hydration temperature (T_{max}) and time (*t*) to reach T_{max} were recorded and two wood-cement compatibility indices, C_A - factor and hydration rate (R) were calculated*:*

R= (T_{max} - T_{min})/t.

$T_{min:}$ Temperature attained during the time when not more than three repeated values are recorded.

$$C_A = \frac{A_1}{A_2} * 100$$

Where, A_1 : Area under the wood-cement sample hydration curve, A_2 : Area under the control sample curve.

Control sample is made with cement only. Then, wood species were classified as compatible, moderately compatible or incompatible with cement based on the extent to which they delayed cement hydration (Hachmi et al., 1990).

Mechanical tests on moulded blocks

The evaluation of the aptitude of mixes to wood work by measuring cement hydration temperature and compatibility indices has been completed by mechanical tests on moulded blocks. Thus, sawdust and fibers treated in hot water, cement and water were mixed respecting the following ratio:
sawdust/fibers/cement/water mass ratio of 60/15/1000 /452.5 g according to the ratio adopted in the work of Andy and Land Zhongli (1986) in which total mass of wood was 75 g.

For each batch of mix, twelve cubic specimens (50 x 50 x 50 mm) were used to conduct compressive tests after 28 days of curing in water in room at 20-25°C.

Mechanical tests on wood-cement composites

The sawdust, vegetable fibers, cement and water were mixed according to the most convenient ratio for wood species. For all species, the wood/cement ratio in weight was about 0.80 as found in the work of Tchehouali (2002), but the water/cement ratio in weight varied as indicated in Table 1 with consistency test in fresh mixtures.

The mixes was placed in steel mould and compacted. For each batch of mixture, twelve cubic specimens (50 x 50 x 50 mm) and twelve cylindrical specimens with diameter: 50 mm and height: 100 mm were used to conduct compressive and indirect tensile (split tensile) tests, respectively. After 24 h, the boards were de-clamped and conditioned for 28 days at 20°C and 65% relative humidity

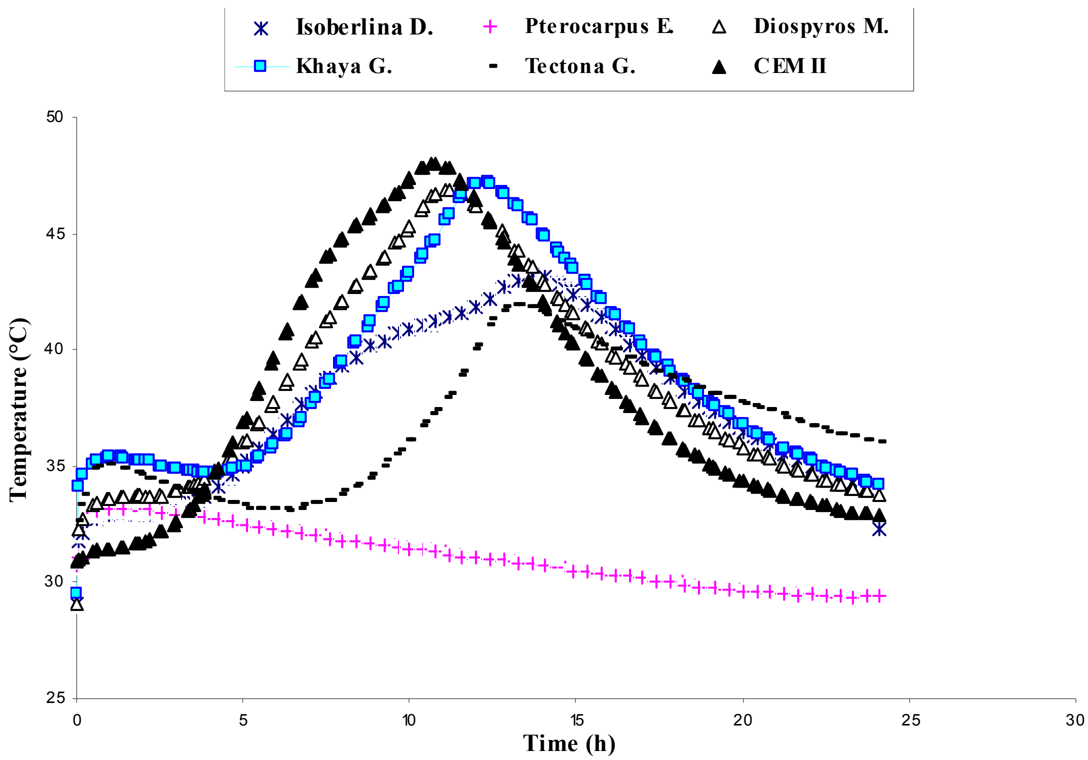

Figure 2. Hydration exotherms (temperature vs. time) for neat cement1 and cement containing tropical wood treated with cold water.

Table 2. Compatibility indices of tropical wood species treated with cold water.

Mix	T_{max} (°C)	T_{min} (°C)	Time (H)	Rate (°C/H)	C_A factor (%)
CEM II	47.8	31.5	8.5	1.80	100
CEMII + *Diospyros mespiliformis sawdust* + *Eleais guineensis* fibers	45.9	34	7.95	1.58	63
CEM II + *Isoberlina doca sawdust* + *Eleais guineensis* fibers	42.8	33.1	10.31	1.0	60
CEM II + K*haya grandifoliola* sawdust+ *Eleais guineensis* fibers	46.3	34.1	7.09	1.72	54
CEM II + Tectona grandis sawdust+ *Eleais guineensis* fibers	41.2	33.0	5.29	1.54	47
CEM II + P*terocarpus erinaceus* sawdust+ *Eleais guineensis* fibers	0.0	0.0	0.0	0.0	0.0

(RH) to allow the cement to cure and gain strength.

Tensile and compressive tests were carried out directly on half of the samples while others were tested after they were soaked in water at laboratory room temperature (20°C) for 24 h. After soaking, the samples were drained on paper towels for 20 min to remove excess water. Tensile and compressive tests constitute simple and relevant mechanical tests on wood cement - composites to quickly evaluate the aptitude of wood specie for wood work.

RESULTS AND DISCUSSION

Compatibility of wood species with cement based on measurements of cement hydration temperature and compatibility indices.

From Figure 2, when the mixes of sawdust and *E. guineensis* fibers were treated with cold water, the curves indicate that in the mixture of *Isoberlina doka* and *Diospyros melsiformis* species, hydration reactions started very earlier (about 3 hours after adding water) than in other mixtures. In the mixtures of *Tectona grandis* and *Khaya grandifoliola* species, hydration reactions started about 7 and 5 h, respectively. The curve corresponding to *Tectona grandis* species presented a great and favourable tendency in developing heat hydration even over 30 h.

From Table 2, *Isoberlina doka* and *Diospyros melsiformis* species have yielded the highest compatibility indices with C_A - factor equals to 60 and 63%

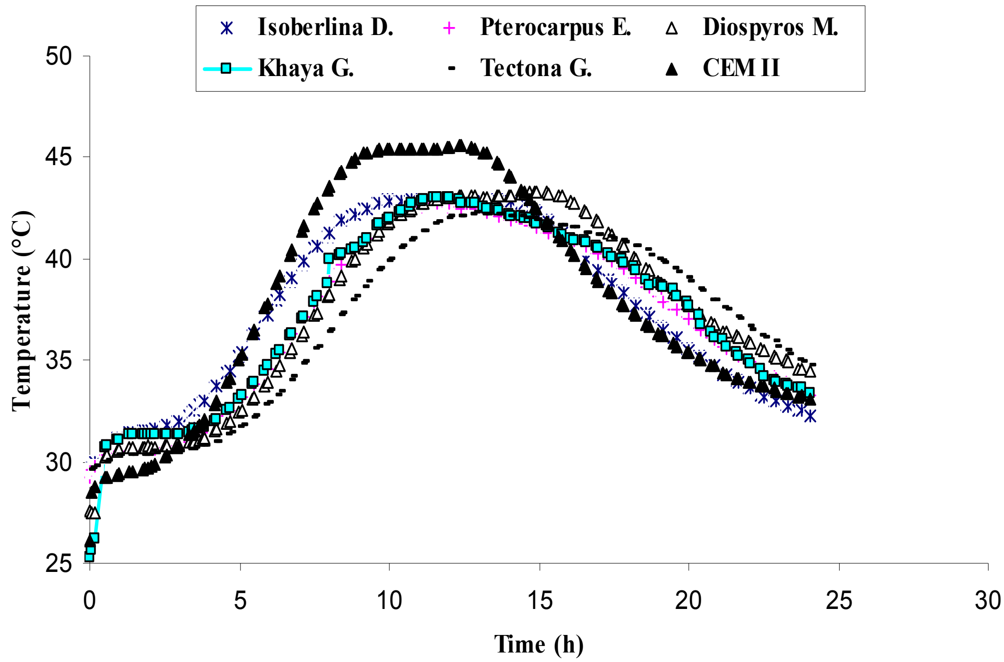

Figure 3. Hydration exotherms (temperature vs. time) for neat cement and cement containing tropical wood and fibres treated with hot water

Table 3. Compatibility indices of tropical wood species treated with hot water.

Mix	T_{max} (°C)	T_{min} (°C)	Time (H)	Rate (°C/H)	C_A factor (%)
CEM II	45.4	31.3	8.5	1.56	100
CEM II + *Isoberlina doca sawdust* + *Eleais guineensis* fibers	42.9	32.1	6.92	1.56	80
CEM II + K*haya grandifoliola* sawdust+ *Eleais guineensis* fibers	41.4	31.8	6.75	1.42	72
CEM II + P*terocarpus erinaceus* sawdust+ *Eleais guineensis* fibers	42.7	31.5	7.26	1.54	70
CEM II +T*ectona grandis* sawdust+ *Eleais guineensis* fibers	42.3	31.3	8.17	1.55	73
CEMII + D*iospyros mespiliformis sawdust+ Eleais guineensis* fibers	41.4	31.8	6.67	1.51	66

respectively. *K. grandifolila* and *T. grandis* species had C_A- factors equal to 54 and 47%, respectively. There is no data in the columns corresponding to *Pterocapus erinaceus* species because of its great inhibitory effect on the cement hydration.

From Figure 3, in the case of hot water treatment, the curves of the mixtures of *I. doka* and *K. grandifolila* species show earliest hydration reactions starting from about 2.20 and 3.75 h, respectively after mixing with water. The mixtures of *T. grandis*, *P. erinaceus* and *D. melsiformis* species started their hydration reactions about 4.10, 5.20 and 6.10 h, respectively after mixing with water. In spite of a long delay in starting hydration reactions, *T. grandis* specie had good compatibility indices as indicated in Table 3. *Isoberlina doka*, *Tectona grandis*, *Khaya grandifolila* and *P. erinaceus* species had average C_A - factors equal to 80, 73, 72 and 70%, respectively. The lowest compatibility indices were provided by *Diospyros mespiliformis* (C_A - factor equals to 66%).In general, the results indicate that the treatment of sawdust and fibers in hot water enhance notably the compatibility indices of all species as found in previous work of Alberto et al. (2000).

With simple treatment in cold water, *Isoberlina doka, Diospyros melsiformis* and *K. grandifolila* species had good compatibility indices while compatibility indices of *T. grandis* and *P. erinaceus* species were negatively affected. Alberto et al. (2000) had a similar report on *Khaya* specie which indicated that *P. angolensis* and *K. nyasica* species were compatible with cement after simple treatment in cold or hot water. The contrast of the findings about *P. angolensis* species could be due to the presumed change of the nature of soil where the species has been grown.

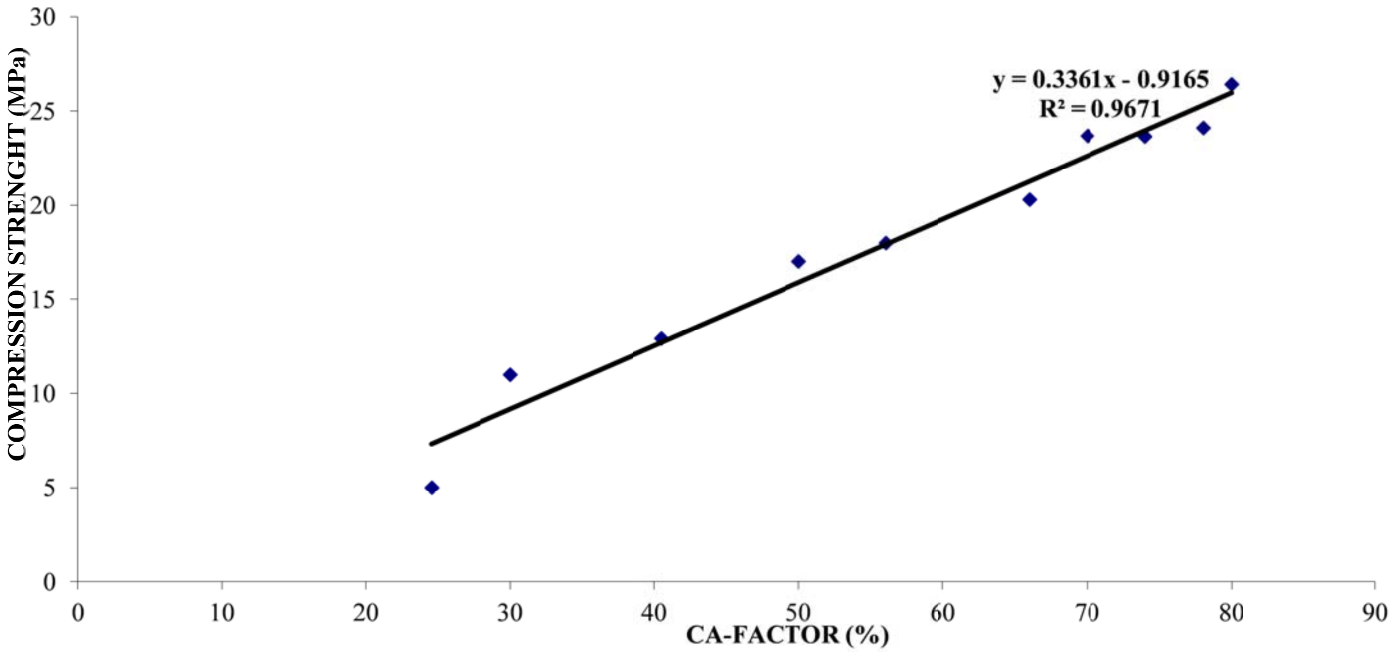

Figure 4. Evolution of compressive strengths of moulded blocks with C_A-factor.

Characteristics of moulded blocks

The blocks have presented an average density of about 1395 kg/m^3. They could not be classified as lightweight concretes which densities vary from 450 to 1200 kg/m^3 (Mougel, 1992). The very slight variation of the densities (minimum value 1310 kg/m^3 corresponding to *Pterocarpus eurinaceus* species and maximum value 1370 kg/m^3 corresponding to *Isoberlina doka* species tallies with the slight variation of the characteristics of the blocks as shown in Figure 4 whereby compressive strengths vary from 21.5 MPa for *P. eurinaceus* species to 24.0 MPa for *I. doka* specie. Moreover, from Figure 4, compressive strengths values were linearly proportional to C_A- factors and such results lead to the conclusion that physical tests could be a real indicator of wood-cement compatibility (Andy and Land Zhongli, 1986). The great proportion of cement in the blocks and the relative high densities obtained constitute a major inconvenience when such material is used as lightweight material with low cost. The compressive tests were carried out on the blocks only to establish the correlation between strengths and C_A - factors.

Mechanical strengths of wood -cement composites

In the case of cold water treatment, the highest mechanical strengths of wood-cement composite were obtained with *I. doka* and *D. mespiliformis* species both in dry and wet conditions as shown in Figure 5. *P. eurinaceus* species provided the lowest mechanical strengths.

In the case of hot water treatment (Figure 6), *I. doka* and *T. grandis* species showed the highest strengths. Samples made from *T. grandis*, *P. eurinaceus* and *K. grandifoliola* species presented good strengths both in dry and wet conditions. *D. mespiliformis* species provided the lowest mechanical strengths. The tensile and compressive strengths of wood-cement composites were very low and decreased drastically in wet conditions (about 40%) especially with *I. doka* and *D. mespiliformis* species.

The term compatibility refers to the degree of cement setting after mixing water, wood and fibers. The performance of specific wood species depends on the chemical composition of their extractives which could be extracted with simple cold water or hot water treatment. Several works (Hachimi et al., 1990; Alberto et al., 2000; Balkis et al., 2012; Weatherwax et al., 1964) indicate that before elaborate wood-cement composite, sawdust should be treated in cold or hot water but treatment in hot water is more efficient than treatment in cold water because hot water act more deeply on the extractives. Thus, some wood species may require a more severe treatment, in NaOH 1% solution for example, in order to overcome their incompatibility with cement. The very low strengths presented in Figures 5 and 6 especially in cases of *P. erinaceus* and *D. mespiliformis* species indicate that more severe treatment should be applied before their utilization as building material in construction. Several other techniques exist to be explored in the next investigations to enhance the mechanical characteristics

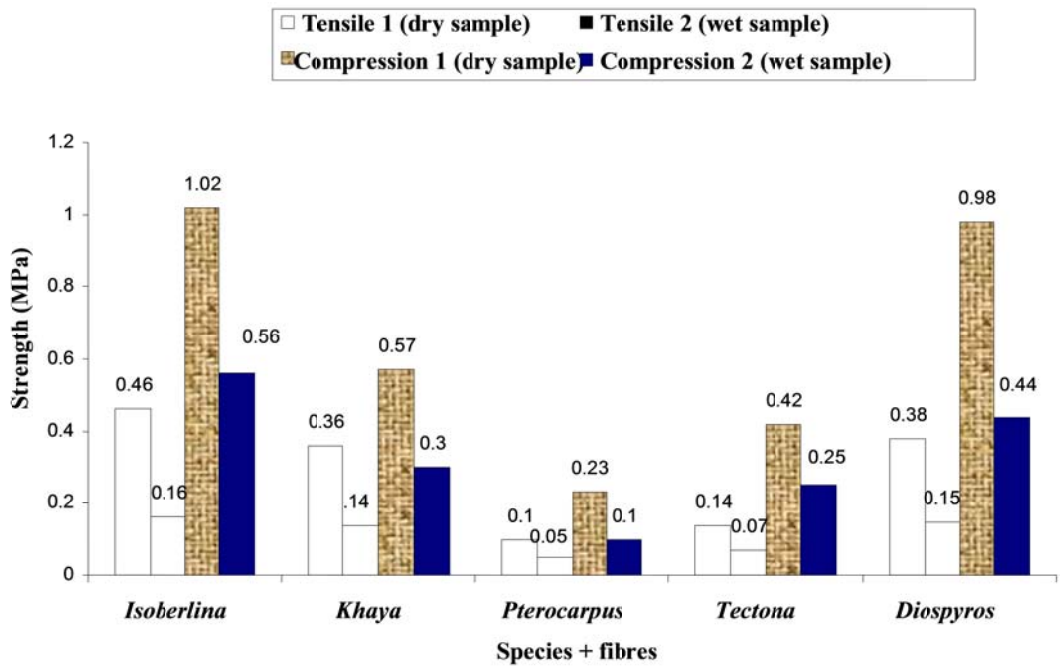

Figure 5. Tensile and compressive strengths of wood cement composites (treatment in cold water).

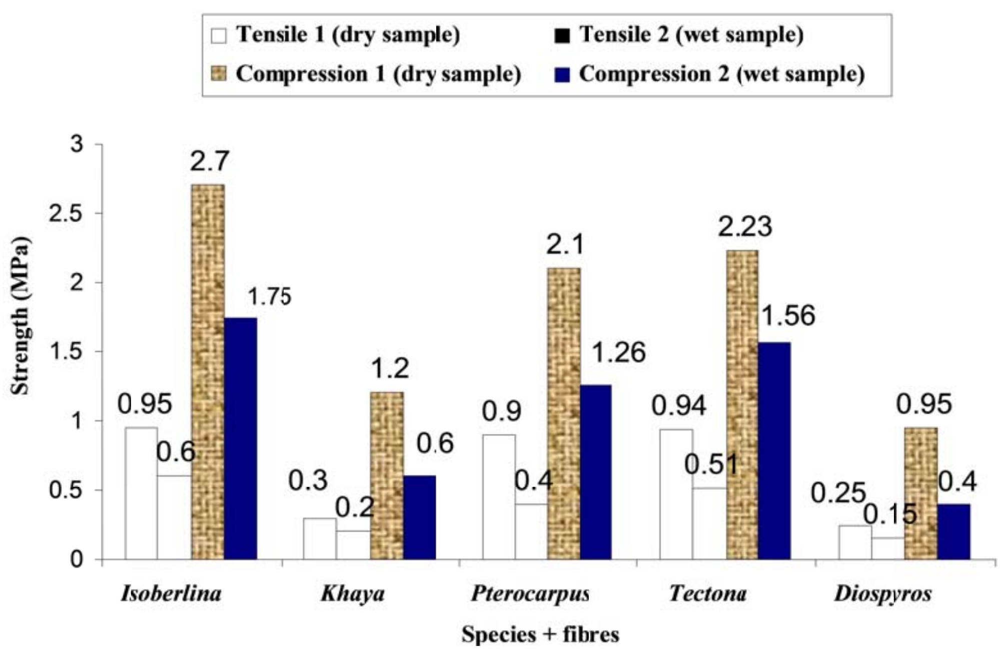

Figure 6. Tensile and compressive strengths of wood-cement composites (treatment in hot water).

of the wood-cement composite made from sawdust and vegetable fibers available in Benin. The new material can be used to manufacture lightweight bricks for walls.

Conclusion

In this study, the sawdust from five West African wood species partially replaced by *E. guineensis* fibers were tested to make wood-cement composites. The compatibility study indicated that all the sawdust and fibers mixes have good aptitude to wood-cement composites. After hot water treatment which enhanced the compatibility of the most mixes, only *Diospyros mespiliformis* species became moderately compatible with cement while the other species namely Isoberlina *doka*, *T.grandis, K. grandifoliola* and *P. erinaceus* species had good compatibility with cement. *T. grandis* and *P. erinaceus* sawdust containing *E. guineensis* species were greatly affected by cold water treatment.

The study confirms that physical and mechanical tests on wood-cement composites could provide quick and satisfactory results to assess the aptitude of tropical hardwood species for wood work. On the basis of the density and compressive strengths of wood-cement composite, the main factor of compatibility of the wood specie with cement could be approximately and quickly evaluated.

In wet conditions, the mechanical strengths of wood-cement composites decrease drastically (about 40%), especially *I. doka* and *D. mespiliformis* species. Such important result must be taken into account when using the composites in a humid environment. Finally, one can suggest the most suitable mixes of fibers and the five West African hardwood species for wood-cement composite in the following order: *I. doka*, *T. grandis, K. grandifoliola*, *P. erinaceus* and *D. mespiliformis* species. Tests will continue to be done in order to find the best way to keep very low the inhibitory effect of the wood species and the fibers on the cement hydration.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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