NATURE AND PERFORMANCE OF TROPICAL WOOD NATURAL FIBRE CEMENTITIOUS COMPOSITES

PROFESSOR DR MIZI FAN, DR MAURICE KOR NDIKONTAR AND PROFESSOR JOHN DINWOODIE

Head of Research, Department of Civil Engineering, Brunel University, UB8 3PH, UK.

ABSTRACT

The 12 commercially available tropical wood natural fibre species and their cementitious composites were thoroughly studied for possible production of natural fibre cementitious composites (NFCC), through 1) the determination of chemical constituents of the fibre species, 2) determination of compatibility of natural fibre cement and correlation of the compatibility with chemical constituents, and 3) examination of mechanical property of NFCC and its correlation with the compatibility and chemical constituents of wood natural fibres. The results showed that 1) the chemical constituents of the 12 tropical wood fibrous materials varied considerably from one to another fibre species, with cellulose content ranging between 40 and 57%, lignin between 21 and 34% and solubility between 2.40 and 29.06% depending on the type of solutions. 2) pH values were below 7 for all natural fibres tested (pH 3.36-6.22) and the ABR values were no more than 1, indicating that the BBC values were higher than the ABC values. 3) The compatibility reduced as the wood natural fibre content increased and was polynomially correlated to the solubility of the wood natural fibre species. 4) Mechanical properties of NFCC decreased with increased fibre content, with the highest bending strength (7.21 MPa) and compressive strength (33.18 MPa) for movingui NFCC corresponding to the lowest hot water and $Ca(OH)_2$ solubility, and lowest bending and compressive strength (0 MPa) for both moabi and doussie NFCC to their highest solubility contents. 5) The best five natural fibre species studied for NFCC were movingui, nkanang, eyong, tali and padauk, while the least suitable two were moabi and doussie. The results have provided fundamental and essential database and technologies for better understanding tropical wood natural fibre species, utilising them as value added commercial products in construction industry and further academic research.

KEYWORDS:

Tropical wood natural fibre; chemical constituents; cement; compatibility; natural fibre cementious composite.

INTRODUCTION

Unreinforced cementitious materials are characterised by low tensile strength and strain capacities and therefore require reinforcement to achieve load bearing capacity requirements for construction application. This reinforcement has historically been in the form of continuous reinforcing bars to withstand the imposed tensile or shear stresses. Fibres on the other hand are discontinuous and are most commonly randomly distributed in cementitious matrix. They are not as efficient as the steel bars in withstanding the tensile stresses, but tend to be more closely spaced and are more effective in controlling cracking. Compared with traditional concrete, natural fibre reinforced cementitious composite (NFCC) can reduce material cost, reuse wood wastes, and improve thermal performance of conventional concrete panels while preserving a certain level of mechanical qualities [1]. The use of wood NFCC has also many advantages over other conventional wood materials. These include better insulation and fire performance, better resistance to water soaking, better bactericidal properties so that it prevents micro-organisms (fungi and insects attack) and mycelium growth, and higher stiffness [2-3]. In addition to a wide spread of uses as flat roofing, prefabricated structures, mobile homes, permanent formwork, cladding, sound barriers and paving, NFCC lends itself to SIP (structural insulation panel) construction in the modern method of construction in the developed countries and low-cost housing systems in the developing countries because of 1) their relatively low cost since the wood used is either sawmill rejects or wood unsuitable for sawmills and both wood and cement are readily available; 2) low production investment and simple technology required; 3) the low weight of boards which makes handling easier without cranes compared to steel and bricks and 4) no volatile organic compound release as is the case with resin-bonded boards. Natural fibres are prospective reinforcing materials; however, the development of NFCC has been slowed down by a lack of basic understanding of the mechanisms involved in the bonding of cement and wood. Among mechanical and chemical bonding mechanisms, the latter has aroused much debate [4]. Wood natural fibre contains many inhibitory substances (e.g. hemicelluloses, starches, sugars, phenols, hydroxylated carboxylic acids). These substances may dissolve and affect wood natural fibre cement hydration and cement crystallization [5-6]. Moreover, different wood fibre species with the same quantity of extractives may have very different compatibilities due to chemical composition of wood fibre extractives [7]. Among many other bonding mechanisms [8], the 'poisoning' mechanism of cement by the substances extracted from natural fibres under the alkaline environment of cement is very complicated which is subtly related to the age of wood, exposure time of wood natural fibres, wood natural fibre species, geological environment and seasons. The performance of NFCC could be directly related to the wood natural fibre species and compatibility. The mechanical property and maximum hydration temperature (MHT) of NFCC has been used to characterise the suitability of the wood natural fibres matrix for the production of NFCC [9-11].

Most of the wood species investigated in this study are abundant resources in many African or South American countries and exported to many other countries around the world. However, these materials are so far underutilised in construction industry. The fundamental information and technologies are urgently required for further research or fully utilising these tropical wood species for engineering products. This paper aims at providing a fundamental essential database and technologies for exploiting tropical wood species with cement and better utilising them as value added commercial products in construction industry.

MATERIALS AND METHODS

Natural fibres

The 12 different types of natural fibres/wood species are studied for possible use for the production of NFCC. The wood species were harvested in the same month of a summer season from a well-developed dense humid forest ecological zone between latitudes 1° and 7° north, one of the four ecological zones of Cameroon. They are ayous wood (triplochiton scleroxylon), doussie (afzelia pachyloba), eyong (eribroma oblongum), frake (terminalia superba), iroko (chlorophora excelsa), moabi (daillonella toxisperma), mouvingui (distemonanthus benthamianus), ngollon (khaya ivorensis), nkanang (sterculia rhinopetala), padauk (pterocarpus soyauxii), sapele (entandrophragma cylindricum) and tali (erythrophleum ivorense). Three wood discs, each 100mm thick, were cut from each wood species with one at 1 m from both ends, respectively, and one from the middle of a wood log randomly selected from a pile of each species available at the CORON mill in Yaounde. The discs were allowed to dry in the air and then chipped to obtain wood particles which were further broken down to fine fibres and powders by using a Retsch SM 100 3-blade cutter miller and sieved on AFNOR NF X 11-501 sieves. The wood fibrous materials that passed through a 0.400mm sieve but retained on a 0.160-mm sieve were used for the chemical characterisation, pH and buffering capacity measurements. Those that passed through a 0.800-mm sieve but retained on a 0.400-mm sieve were used for NFCC fabrication [12]. The aspect ratios of these fibrous materials are low, ranging from 22 to 62. The wood natural fibres were then stored under an environment of 20°C and 65% relative humidity before use. Five replicates were used for each test for each experiment unless otherwise specified.

Composition of the natural fibres studied

The characterisation of chemical constituents of the fibrous materials (wood species) was carried out by using TAPPI standard test methods [12-13], including i) the alcohol-benzene extract, ii) the hot water extract, iii) the 1% NaOH solubility, iv) the Klason lignin content, v) the Kürschner cellulose content and vi) the saturated lime solution solubility. The chemical reagents used were purchased from market and used without further purification. The chemical constituents were calculated against the oven-dried untreated fibrous samples as follows:

$$\%\,\text{cellulose} = \frac{m_r\,(100-\%AB)}{m_s\,(100-\%H)} \times 100 \quad (1)$$

$$\%\,\text{lignin} = \frac{m_r\,(100-\%AB)}{m_s\,(100-\%H)} \times 100 \quad (2)$$

$$1\%\ \text{NaOH solubility} = \left(1 - \frac{m_r\,(100-\%AB)}{m_s\,(100-\%H)}\right) \times 100 \quad (3)$$

$$\text{hot water solubility} = \left(1 - \frac{m_r\,(100-\%AB)}{m_s\,(100-\%H)}\right) \times 100 \quad (4)$$

$$\text{alcohol/benzene solubility} = \left(1 - \frac{100\,m_r}{m_s\,(100-\%H)}\right) \times 100 \quad (5)$$

$$\text{solubility in saturated lime solution} = \left(1 - \frac{100\,m_r}{m_s\,(100-\%H)}\right) \times 100 \quad (6)$$

Where, m_r is the mass of residue in the filtering crucible, %AB is the alcohol-benzene solubility of untreated fibrous materials, m_s is the mass of fibrous sample weighed and %H is the moisture content of the fibrous sample at room temperature.

To determine the pH and buffering capacities, 25g of fibrous flour (oven-dry basis) were mixed with 250mL of distilled water. The mixture was heated under reflux for 20 minutes to boil and then the extract filtered using a water aspirator. After cooling, 50mL of the extract were taken for its pH determination by using a standardised Schott Geräte digital CG818 pH-meter. The solution was then titrated either with a 0.025N solution of sodium hydroxide (NaOH) (to a pH of 7) to determine its acid buffering capacity (ABC) or with a 0.025N solution of sulphuric acid (H_2SO_4) (to a pH of 3) to determine the base buffering capacity (BBC). Four replicates were taken and the average is reported.

Compatibility of natural fibres with OPC

The compatibility of the natural fibre materials with cement was determined by examining the hydration characteristic of OPC in various natural fibrous materials. The study was carried out by using double-walled Dewar flasks with type K thermocouples connected to an ANRISTU 7200 multi-point recorder to monitor the temperature inside the Dewar flasks as a function of time conforming to BS 4550-3.8: 1978 – Methods of testing cement – Part 3: Physical tests – Section 3.8 Tests for heat of hydration. The process was carried out by hydrating 200g cement with different volumes of distilled water and the amount of wood powder of each species was also increased in order to determine the effect of wood content on compatibility. The required mass of all constituents was thoroughly mixed in a small polythene bag and each bag was then wrapped in aluminium foil and placed in the Dewar flask. The thermocouple probe was pushed to the centre of the mixture through a short copper pipe. The Dewar flask was completely closed with styro-foam. The temperature versus time curves of cement-water, natural fibre-cement-water mixtures and the ambient atmosphere were simultaneously and automatically plotted on the recorder which was able to take six readings simultaneously.

Fabrication of NFCC

Composed Portland cement (CPJ 35) from CIMENCAM (Cameroon) and the required amount of wood natural fibrous materials (10% oven dry weight) were thoroughly mixed for 2 minutes. This combination was chosen to simulate industrial conditions for cementitious composite manufacture [14]. The water-to-cement ratio of 0.35 plus 1 g of water per gram of fibrous materials was used. The fibre-cement paste was further mixed for 2 minutes and then transferred into 40x40x160mm moulds which had been previously lubricated with clean engine oil to allow easy de-moulding. The filled moulds were then vibrated for 5 minutes on an electricallyvibrated table to ensure a good packing. The mixtures were allowed to harden for 48hours before de-moulding. The de-moulded composites were further cured in sealed polythene bags with 100% humidity for 28 days before mechanical testing. The neat cement panels were also made as a control.

Measurement of mechanical properties

The natural (wood) NFCC were subjected to a three-point bending tests with Universal Instron. The span was 106.7mm [15-17]. 12 replicates were used. The compression test pieces were sampled from both ends of the used bending test pieces. 24 replicates for each type of composites were used.

The bending strength, σ_{max}, is calculated by:

$$\sigma_{max} = \frac{3}{2}\frac{FL}{bh^2} \qquad (7)$$

The compression strength, Υ_{max}, is defined by:

$$\Upsilon_{max} = \frac{N}{S} \qquad (8)$$

Where, F is the maximum failure load, L is the span, b is the width of the test pieces, h is the thickness of the test pieces, N is the maximum compressive load and S the cross section area.

RESULTS AND DISCUSSION

Chemical constituents of natural fibrous materials

The chemical constituents of aggregates, i.e. natural wood fibres in this study, have an influence on the properties of cementitious composites: Cellulose content of natural fibres could enhance the mechanical property of fibre-cement composites, while other constituents, e.g. lignin and other low molecular weight carbohydrate contents, may result in an adverse effect on the processing and compatibility of NFCC.
The chemical constituents of the 12 fibrous materials studied are summarised in Table 1. It can be seen that the cellulose contents range between 40 and 57% and lignin between 21 and 34%. Tali, iroko, eyong and padauk have cellulose content over 50%, while the rest of fibrous materials have relatively lower cellulose content, indicating that the former may result in higher property of fibre-cement composites.

However, the amount of low molecular weight carbohydrates or lignin, i.e. the percentage solubility in 1% sodium hydroxide, hot water, alcohol benzene or saturated lime varies considerably from one to another species. This could contribute a significant effect on the compatibility of fibres with cement. An addition of the solubility in hot water and saturated lime, which are two of the exposing conditions when fibres were mixed with cement, gives rise to a ranking order of the solubility, moabi>iroko>doussie>padauk>eyong >frake>ayous>ngollon>tali>sapele>nkanang>movingui. The highest solubility (22.34%) is more than three times lowest solubility (7.10%), indicating that the former fibre may be much compatible with cement compared to the latter fibre.

Table 1 - Chemical constituent of fibrous materials (%)

Wood species	Cellulose	Lignin	NaOH sol.*	H_2O sol.*	Me(OH) sol.	$Ca(OH)_2$ sol.	$[H_2O+Ca(OH)_2]$	Ash
Ayous	44.16	33.52	16.67	4.94	3.13	6.74	11.68	1.62
Tali	56.24	32.87	29.06	5.66	6.10	4.00	9.66	0.05
Iroko	51.50	29.94	26.32	8.64	7.87	10.26	18.90	2.93

Fraké	47.81	31.00	18.35	5.02	3.18	8.71	13.73	3.18
Eyong	52.00	21.60	19.00	6.10	2.40	10.38	16.48	1.25
Moabi	44.50	29.80	17.50	11.10	10.40	11.24	22.34	0.43
Nkanang	45.20	25.40	14.80	3.70	4.20	3.50	7.20	1.87
Padauk	53.13	30.48	21.52	5.84	12.33	10.83	16.67	0.82
Sapele	45.80	31.10	19.80	5.90	3.40	3.26	9.16	1.48
Doussie	39.80	27.30	16.70	2.40	15.60	16.30	18.70	0.78
Ngollon	48.81	27.57	25.80	5.56	5.94	4.26	9.82	1.20
Movingui	42.90	28.80	18.10	2.50	7.40	4.60	7.10	1.12

*NaOH=1%NaOH; H_2O=Hot water; sol.=solubility

Buffering capacity of natural fibrous materials

The acid buffering capacity (ABC) value was calculated based on the amount of 0.025N NaOH (V_B in millilitre) required to raise the pH of 50mL water extract of the fibrous (wood species) to 7.0, as defined by Lambuth [18]:

$$ABC\ 8\ 0.025 Z V_B \qquad (9)$$

With the same principle, the base buffering capacity (BBC) was calculated based on the amount of 0.025N H_2SO_4 (V_A) required to bring the pH down to 3.0:

$$BBC\ 8\ 0.025 Z V_B \qquad (10)$$

The values V_A and V_B can be obtained by drawing a curve of pH versus the volume of acid or base (Figure 1). The total buffering capacity (TBC) was calculated as the sum of the acid and the base buffering capacities (ABC+BBC). The acid-to-base ratio (ABR) is the ratio of ABC to BBC:

$$ABR\ 8\ \frac{ABC}{BBC} \qquad (11)$$

The pH, buffering capacity, acid-to-base ratio values of fibrous materials investigated are given in Table 2. It is apparent that the pH values vary considerably from one species to another. All pH values are below 7, ranging from the lowest 3.36 for tali to the highest 6.22 for iroko. These values fall well within the pH range reported for temperate hard and soft woods [19]. However, these values are slightly different from those that had been measured when the species were just harvested and fresh [20]. This may be due to the partial breaking down of low molecular weight carbohydrates. This is in line with the report that air-dried wood was more compatible with cement than cold-stored wood [21] and that long storage enhances compatibility of wood and cement [22-23]. The pH value will have an influence on the fibre-cement reaction by considering that the cement hydration results in highly alkaline hydrate products.

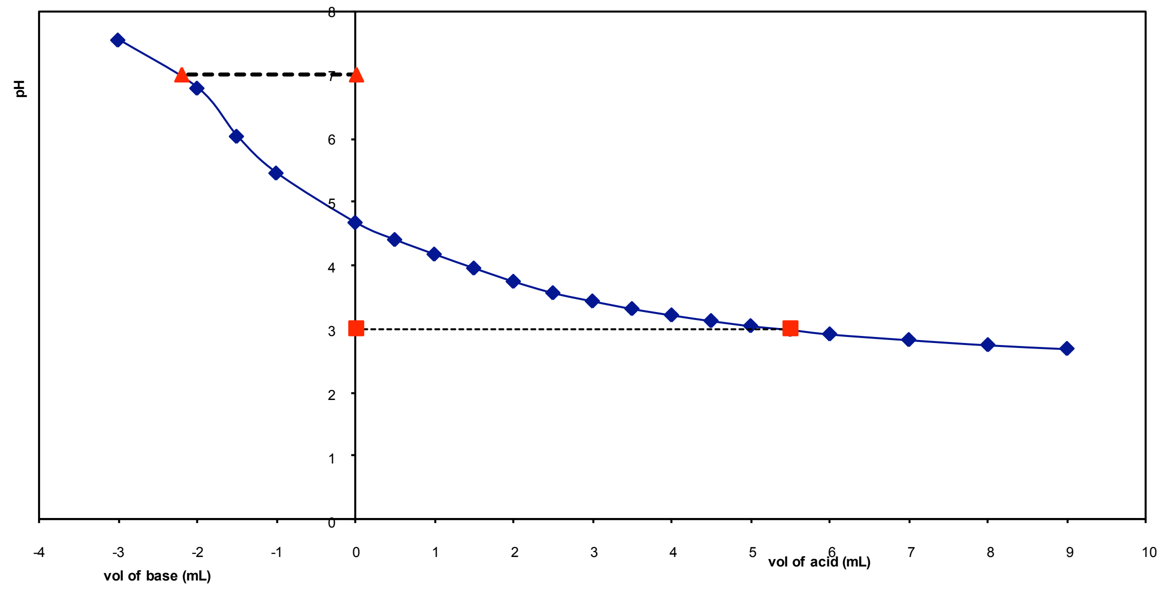

Figure 1 - Variation of pH of hot water extract of Nkanang when acid or base solution is added

It is most interesting that the ABC value is the highest for tali and the highest BBC value is for iroko as the former species has a lowest pH and the latter has a highest pH among those species investigated (Table 2). The rest of fibres follows the similar tend although without exact correlation.

Except tali which has the highest ABR value of 5.67, the ABR values for the fibrous materials tested are generally no more than 1 (Table 2), indicating that the BBC values are higher than the ABC values and the majority of extracts revolves at pH around 4.

pH and buffering capacity are important in understanding the interface of natural fibre and cement. Extreme values of wood pH have been reported to be troublesome for achieving good adhesive bonds [24-25]. The gelation times were reported proportional to the pH but inversely proportional to acid buffering capacity [18]. These results will have an influence on the cement hydration behaviour of the various fibrous materials.

Table 2 - pH and buffering capacities of fibres (wood species)

Species	pH	ABC	BBC	TBC	ABR
Ayous	5.60	1.3	9.3	10.6	0.14
Tali	3.63	17.0	3.0	20.0	5.67
Iroko	6.22	5.0	72.5	77.5	0.07
Fraké	5.79	4.2	18.5	22.7	0.23
Eyong	5.82	1.5	11.7	13.2	0.13
Moabi	4.67	2.4	4.6	7.0	0.52
Nkanang	4.66	2.3	5.3	7.6	0.43

Padauk	4.15	4.6	4.6	9.2	1.00
Sapele	5.05	2.9	10.3	13.2	0.28
Doussie	4.59	10.0	9.5	19.5	1.05
Ngollon	4.45	4.5	6.5	11.0	0.69
Movingui	4.78	1.8	4.8	6.6	0.38

Correlation of constituents with compatibility of natural fibres and cement

The compatibility of the natural fibres (wood species) was determined by using the area ratio (*C*) method recommended by Hachmi et al [26], and calculated by using:

$$C \quad 8 \; \frac{A_{wc} \, \Psi A_o}{A_c \, \Psi A_o} x100\% \qquad (12)$$

where, A_{wc} is the area under the hydration curve for the wood-cement-water mixture, A_c is the area under the hydration rate curve for the cement-water mixture and A_o is the area under the ambient temperature-time curve in the same time interval (Figure 2). More detailed discussion has been given in a separate paper [27].

The compatibility factor (*C*) as a function of wood natural fibre content in fibre-cement mixture is summarised in Table 3. Overall the compatibility reduces as the wood natural fibre content increases, ranging from 90% to 0% depending on the species and quantity of natural fibres mixed. More details are given in a separate paper [27].

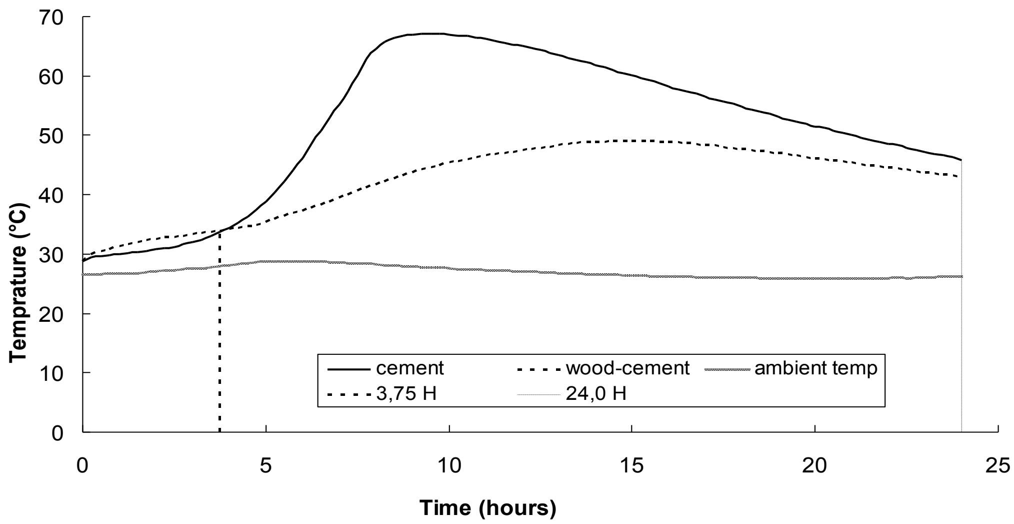

Figure 2 - Area between hydration and ambient temperature curves

As aforementioned, the amount of low molecular weight carbohydrates or hemicelluloses, e.g. the percentage solubility, in chemical solutions could contribute to a significant effect on the compatibility of wood with cement. A comparison of Table 1 and Table 3 indicates that the fact of high NaOH soluble contents for iroko and low NaOH soluble contents for nkanang is in good agreement with the results of the compatibility factor *C* values for these species. However, the NaOH soluble contents in species tali and ngollon may only be one of the factors for the inhibition of wood natural fibre cement mixtures.

The results for the hot water solubility, with the highest being moabi (11.1%) and lowest movingui (2.5%), are again in good agreement with the results of the factor *C* values, i.e., wood fibre-cement compatibility ratios. Higher alcohol-benzene solubility values for moabi, padauk and doussie (>10%) compared to other natural fibre species tested (about 7 %) are also consistent to the results from compatibility test. The solubility in saturated $Ca(OH)_2$ solution is highest for doussie at 16.30%. This solubility ranges from 10 to 11.5% for iroko, bete, moabi and padauk. The rest of the species studied have a solubility of less than 9% in saturated $Ca(OH)_2$ solution. This ranking order is again in good agreement with ranking order of the factor *C* values for these species, reinforcing the effect of the soluble on the hydration/compatibility of cement-wood for NFCC.

The correlation of solubility of natural fibres with the compatibility has been studied. It is evident that the compatibility is closely correlated to the solubility of the wood natural fibre species in saturated lime solution, hot water and alcohol, with the compatibility reducing as the solubility increases. An example of this correlation is illustrated in Figure 3. The correlation can be predicted with a polynomial equation with an excellent degree of fit (R^2=0.91).

The above results also indicate that the compatibility and property of NFCC may be improved significantly after extraction of solubles. The detailed treatment and its effect on the compatibility have been discussed in a separate paper [27].

Table 3 - Compatibility of 12 tropical wood natural fibre species with cement (%)

Wood natural fibre species	Wood content (%)			
	1	**1.8**	**3.5**	**5**
Ayous	75	80	68	54
Tali	90	77	71	58
Iroko	78	65	15	5
Fraké	70	70	64	32
Eyong	75	72	64	54
Moabi	66	41	0	0
Nkanang	98	90	73	72
Padauk	97	90	63	56
Sapele	92	84	73	63
Doussie	55	9	9	9
Ngollon	96	94	77	63
Movingui	99	98	95	90

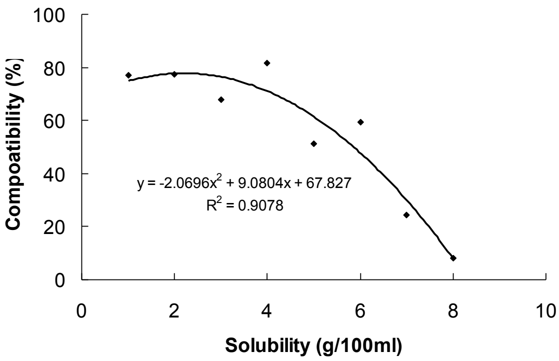

Figure 3 - Compatibility as a function of solubility in saturated lime solution

Correlation of constituents with the properties of NFCC

The bending strength, $□_{max}$, was calculated using the equation 7 above, with the span L = 106.7mm, the width of NFCC b = 40mm and thickness h = 40mm. The compressive stress was calculated by equation (8). Both bending and compressive strength are summarized in Table 4.

It is evident that overall both bending and compressive strengths of NFCC are lower than those of neat cement blocks, indicating that the inclusion of wood natural fibre may result in flaws in the crystal network of hydrated cement paste or/and the fibre constituents, i.e. low molecular weight carbohydrates, may have inhibited the hydration process of cement paste with the natural fibre cement mixture. This is reflected in the different mechanical properties of the NFCC's tested. The highest bending strength is 7.21 MPa for movingui cementitious composite, followed by ayous, sapele and nkanang at 6.63 and 6.51 MPa, and Ngollon, eyong, padauk and tali at 5.94, 5.63, 5.29 and 5.20 MPa respectively. Iroko composites had low bending strength of 3.93 MPa but moabi and doussie composites showed zero bending strength.

The compressive strengths showed a similar trend as that of bending strength: Movingui composites showed maximum strength at 33.18 MPa, iroko composites had the lowest strengths at 12.33 MPa, and Moabi and doussie composites showed zero compressive strength.

However, it must be noted that an addition of wood fibres resulted in a significant reduction of the density of fibre cement composites. This means that the specific bending strength of wood fibre cement composites can be much higher than that of neat cement paste, e.g. 3.44×10^{-3}MPa for neat cement paste and 5.77×10^{-3}MPa for Movingui cement composites respectively. The specific compressive strength are similar for both neat cement paste and wood fibre cement composites, e.g. it is 0.028MPa for neat cement paste and 0.027MPa for Movingui cement composites respectively.

The effect of natural fibres on the mechanical property of their cementitious composites may have resulted from three different aspects: 1) cellulose content within the natural fibre could bring the self-strength into the cementitious composites; 2) the addition of natural fibres in cement paste can improve fracture toughness by blocking flaw propagation, permitting the composite to carry loads to a higher strain limit or to exhibit near-ductile failure [28]; 3) however, the solubles from natural fibres, i.e. low molecular weight carbohydrates, may result in an adverse effect on the hydration process of cement within NFCC depending on the fibre species.

Table 4 - Bending and compressive strength of natural fibre cementitious composites

Natural fibre (Wood) species	$□_{max}$ **(MPa)**	$□_{max}$ **(MPa)**

Neat cement	7.56	61.35
Eyong	5.63	25.36
Movingui	7.21	33.18
Iroko	3.80	12.33
Ngollon	5.94	22.64
Fraké	3.93	13.80
Ayous	6.63	16.63
Sapele	6.63	20.00
Nkanang	6.51	26.34
Tali	5.20	25.23
Moabi	0	0
Padauk	5.29	23.80
Doussie	0	0

Table 5 - R^2 for linear regression of strength against various chemical constituents

Wood natural fibre constituent	R^2	
	Bending strength	**Compressive strength**
% cellulose	0.27	0.40
% lignin	0.02	0.15
% solubility in 1% NaOH	0.11	0.20
% solubility in hot water	0.38	0.41
% solubility in alcohol/benzene	0.68	0.51

% solubility in $Ca(OH)_2$	0.80	0.72
% ash	0.16	0.03
pH	0.04	0.03
ABC	0.27	0.10
BBC	0.13	0.23
TBC	0.19	0.25
ABR	0.02	0.16

A comparison of Table 1 with Table 4 confirmed that the mechanical properties of NFCC are closely related to the solubility of wood natural fibres. Movingui had a lowest total hot water and saturated lime solubility and such movingui cementitious composite had the highest bending and compressive strength. Nkanang had a second lowest solubility among the natural fibre species tested and resulted in compressive and bending strengths of NFCC which were ranked at the second and third among the other composite. Moabi and doussie had the highest solubility, which corresponded to the zero mechanical strength of their NFCC.

The contribution of cellulose to the natural fibre cementitious composites has also been reflected this study. For example, eyong has relatively high solubility, but the eyong cementitious composites had both high bending strength (5.63 MPa) and compressive strength (25.36 MPa) due partly to the high cellulose content (52%).

A linear regression test has been carried out to further examine the correlation between the maximum bending and compressive strengths and the wood natural fibre characteristics examined. The results are summarised in Table 5. The results again showed that both bending and compressive strengths are mostly related to solubility and cellulose content. The R2 for the linear regression of the percentage solubility with saturated lime solution is 0.80 for bending strength and 0.72 for compressive strength, indicating that saturated lime may have dissolved most of the extractives and sugars which are responsible for hydration inhibition. During the hydration of natural fibre cement mixtures, the medium may get saturated in $Ca(OH)_2$ which would then dissolve inhibitive extractives and sugars [29-30]. This is also illustrated in alcohol-benzene and hot water solubility, which are also correlated to the mechanical properties, with R2 being 0.68 and 0.38 for bending strength, and 0.51 and 0.41 for compressive strength respectively. The regression has also indicated the influence of cellulose on the mechanical strength of NFCC. However, there is no clear correlation observed between the other characteristics of natural fibres with the mechanical strength of NFCC (Table 5).

CONCLUSION

The chemical constituents of 12 tropical wood species, their correlation with the compatibility of cement-fibre, and bending and compressive strength of natural fibre cementitious composites (NFCC) have been studied for possible use for the production of NFCC. Specific outcomes can be concluded as follows:

i) The chemical constituents of the 12 tropical wood materials studied varied considerably from one to another fibre species, with cellulose content ranging between 40 and 57%, lignin between 21 and 34%. The ranking order of low molecular weight carbohydrates in 1% sodium hydroxide, hot water, alcohol benzene or saturated lime was moabi>iroko>doussie>padauk>eyong>frake>ayous>ngollon>tali> sapele>nkanang>movingui, with the highest (22.34%) being more than three times lowest solubility (7.10%).

ii) pH values were below 7 for all natural fibres tested, ranging from the lowest 3.36 for tali to the highest 6.22 for iroko. The ABC value was highest for tali and the highest BBC value for iroko. The ABR values for the fibrous materials tested were no more than 1, indicating that the BBC values are higher than the ABC values.

iii) Overall the compatibility reduced as the wood natural fibre content increased, ranging from 90% to 0% depending on the species and quantity of natural fibres mixed.

iv) The compatibility was closely correlated to the solubility of the wood natural fibre species in saturated lime solution, hot water and alcohol, with the compatibility reducing as the solubility increased and the correlation being predicted with a polynomial equation with an excellent degree of fit (R^2=0.91).

v) Mechanical properties of NFCC decreased with an addition of wood fibres depending on wood species. The highest bending strength (7.21 MPa) and compressive strength (33.18 MPa) for movingui NFCC were closely corresponded to the lowest hot water and Ca(OH)2 solubility, and lowest bending and compressive strength (0 MPa) for both moabi and doussie composites were also related to their highest solubility. However, the specific bending strength of Movingui cement composites was 1.7 times higher than that of neat cement paste due to the significant reduction of the density of wood fibre cement composites.

vi) Both bending and compressive strength were linearly related to solubility and cellulose content with a good degree of linear regression fit.

vii) The best five natural fibre species studied for NFCC were movingui, nkanang, eyong, tali and padauk, while the least suitable two were moabi and doussie.

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