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PHYSICAL-MECHANICAL CHARACTERISTICS OF CEMENT-BONDED KENAF BAST FIBRES COMPOSITE BOARDS WITH DIFFERENT DENSITIES

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Abstract

This study was carried out to explore the potential of kenaf bast fibres (KBFs) for production of cement-bonded kenaf composite boards (CBKCBs). More than 70% of the KBFs were of size >3.35 mm and length of 31±0.4 mm, therefore, they were used for CBKCBs production. The CBKCBs with the dimensions of 450 × 450 × 12 mm were produced using cement (C): KBF with proportion of (2:1) and different board densities (BD) namely 1100, 1300 and 1500 kg/m^3. The CBKCBs were first cured in a tank saturated with moisture for 7days, and then kept at room temperature for 21 days. Mechanical and physical properties of the CBKCBs were characterized with regards to their modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB), water absorption (WA), and thickness swelling (TS). Results of the tested CBKCBs revealed that the MOR increased while the MOE decreased due to uniform distribution of KBFs. It was found that loading of KBFs has a negative influence on the internal bond (IB) of the CBKCBs; the IB was reduced as KBFs tend to balling and making unmixed aggregates with the cement. These results showed that the CBKCB is a promising construction material that could potentially be used in different structural applications due to their good mechanical characteristics.

Keywords: Kenaf bast fibres, Board density, Mechanical properties, Dimensional stability.

Nomenclatures

A	Cross sectional area of the specimen
b	Mean width of the tested specimen
C	Weight of cement
d	Mean thickness of the tested specimen
L	Span between centres of support
m_1	Weight of the tested specimen before immersion
m_2	Weight of the tested specimen after immersion
MC	Moisture content
P	Maximum load for the tested specimen or Probability
t_1	Mean thickness of the tested specimen before immersion in water
t_2	Mean thickness of the tested specimen after immersion
W	Weight of KBF
Wt	Weight of water

Greek Symbols

ΔP	Increment in load
ΔW	Increment in deflection corresponding to ΔP

Abbreviations

ANOVA	Analysis of Variance
BS	British Standard
CBKCBs	Cement-bonded kenaf composite boards
IB	Internal bond
KBFs	kenaf bast fibres
LSD	Least Significant Difference
MOE	Modulus of elasticity
MOR	Modulus of rupture
MS	Malaysian Standard
SAS	Statistical Analysis System
TPU	Taman Pertanian Universiti
TS	Thickness swelling
WA	Water absorption

1. Introduction

Asbestos fibres have been widely used in construction industries, but unfortunately, they are considered as a hazardous material which affects the human health. Therefore, due to the health and environmental awareness the academicians and researchers started to find alternative fibres for development of construction materials. Replacement of asbestos fibres by synthetic and natural fibres has been carried out in numerous laboratories [1]. Wood and other vegetable materials in form of fibres or particles have been widely used with cement matrices to manufacture different construction materials [2-3]. Natural fibres are lignocellulosic materials, which are affordable and available abundantly in most tropical and subtropical countries [4]. These natural fibres can be obtained from the leaves, stems, and fruit of the vegetable materials. Recently production of the natural fibres has increased tremendously and the quantity produced by the Asian countries was estimated to be approximately 30 million tons per year [5].

The natural fibres are usually being incorporated into the cement matrix either in discrete or discontinuous forms. The major role of these fibres is to reinforce, i.e., to enhance tensile strength, prevent cracking of the matrix.

Cement-bonded composite was first developed in Europe in 1900 and was comprised of wood particles bonded with magnesite [6]. Portland cement has been the main reinforcing agent used in the production of cement-bonded boards. The production of such boards became commercially important worldwide [7]. There is an increased interest in cement-bonded boards especially in the developing countries [7]. Therefore; researchers have evaluated suitability of different lignocellulosic materials for the manufacture of cement-bonded boards [8-10]. It is a great advantage to use natural fibres as a construction material in the form of cement bonded composite [11].

Recent studies have revealed that coir, coconut husk, sisal, corn stalk, hemp, flax, eucalyptus, and pineapple leaf fibres can successfully be incorporated into cement to produce low-cost building materials [1, 12]. The increased interest in cement-bonded boards is attributed to the widespread availability of major raw materials mainly wood, natural fibres and cement, the enhanced properties of these fibres [13], as well as the availability and simplicity of the technology used for boards production.

The cement-bonded boards produced in Malaysia have been considered to be suitable for building applications, partitioning and floor tiles. The acceptability of these composites is mainly due to their good dimensional stability, high resistance to insect attack, decay and fire, good insulation properties and good nailing ability [14]. However, wood-cement composites such as cement-bonded boards are well suited as the major components of most low-cost housing but their applications started to decrease due to high cost of resins and machinery necessary for their production [15]. It is also necessary to ensure that the strength and properties of the produced boards meet the accepted standards assigned for the wood-cement composites so that they can compete in the local markets.

This study is designed to produce cement-bonded kenaf composite boards and determine the effects of both board density and quantity of kenaf bast fibres on bending, internal bond strength and dimensional stability of the boards.

2. Materials and Methods

2.1. Materials

Kenaf (sp. V36) fibres were obtained from a local plantation source Taman Pertanian Universiti (TPU), Universiti Putra Malaysia, Serdang, Malaysia. Separation of the kenaf bast fibres from the stem was carried out using a decorticator machine. The separated kenaf bast fibres were successfully ground using fiber cutter and screened using a vibrating screen with different pore sizes (0.25, 0.5, 1, 1.4, 2, 2.8, 3.35 and >3.35 mm). Ordinary Portland cement was used as an inorganic binder.

2.2. Method

2.2.1. Fibres size distribution

The fibres size distribution analysis was carried out according to a method reported by Rahim [16]. The fibres are classified into eight different sizes: 0.25, 0.5, 1, 1.4, 2, 2.8, 3.35 and >3.35 mm. However, to depict the actual size distribution, the percentage of KBFs retained in each fraction was calculated based on the initial dry weight. For more accuracy, each measurement was carried out in two replicates. About 100 pieces of individual KBFs were randomly taken from each of these samples for the measurement of fibres length and thickness. The KBFs retained at >3.35 mm sieve was selected to be used in this study since they represent >70% of the screened KBFs.

2.2.2. Manufacturing of CBKCBs

The cement: KBFs ratio used was 2:1, based on the air-dried weight of KBFs. Each board was produced in three replicates with the dimensions of 450 × 450 × 12 mm and at three different board densities of 1100, 1300 and 1500 kg/m3. The calculation for the total amount of water added was based on the Eq. (1).

$$Wt\ = 0.35\,C + (0.30 - MC)\,W \tag{1}$$

where; *Wt* is the weight of water (g), *C* is the weight of cement (g), *W* is the weight of KBF (g) and *MC* is the moisture content. The CBKCBs were produced as follows; the KBFs were first placed in a cement mixer then the predetermined amount of water was added, and they were thoroughly mixed.

A calculated amount of ordinary Portland cement was added and the mixing process continued until a uniform mixture was obtained. The mixture was then manually consolidated into the mould and pressure of 480 kg/cm2 was applied on the boards until 12 mm thickness was reached. The boards were then clamped for 24 hours and hardened under controlled temperature of 65±3ºC inside a hardening chamber. Then the pressure was released and the boards were removed from the moulds. They were first cured in a curing tank at a relative humidity (RH) of 90±5% for about 7 days and then at room temperature and RH of 80±5% for 21 days to ensure a complete hydration of the cement. The mechanical properties (modulus of rapture (MOR), modulus of elasticity (MOE) and internal bonding (IB)), and dimensional stability (water absorption (WA) and thickness swelling (TS)) of the boards were tested according to the Malaysian Standard specification for wood cement boards (MS 934:1986). The testing specification of this standard is almost identical to the British Standard specification for cement-bonded particleboard (BS 5669:1989).

Mechanical properties

Ten samples were used for each test to obtain the average of MOR, MOE and IB. The cured boards were trimmed and cut into different sizes as prescribed in the Malaysian Standards for bending strength with dimensions of 100 mm width, 225 mm length and 12mm thickness Each test specimen was supported horizontally on parallel metal rollers having a diameter of 20-25 mm. The center-to-center spacing of the rollers was 200 mm (16 × thickness of the board to the nearest 25 mm). A load was applied at the center of the tested specimen, until the maximum load was reached. The crosshead speed of the load was set at 3 mm/min in order to ensure that failure occurred between 30 and 120 seconds. The MOR was calculated according to the Eq. (2).

$$MOR\ (MPa) = \frac{3PL}{2bd^2} \tag{2}$$

where P is the maximum load for the tested specimen (N), L is span between centres of support (mm), b is the mean width of the tested specimen (mm), d is the mean thickness of the tested specimen (mm); The calculation of the MOE was made based on the Eq. (3).

$$MOE\ (\text{MPa}) = \frac{L^3 \Delta P}{4bd^3 \Delta W} \tag{3}$$

where, L, b, d are stand for span, width and thickness, respectively as mentioned in Eq. (2)., ΔP is the increment in load (N), ΔW is the increment in deflection (mm) corresponding to ΔP. The internal bonding specimens were prepared with dimensions 40 × 40 mm. The dimensions and weight of each tested specimen were taken prior to gluing on both surfaces, which were then sandwiched between two metal blocks. The specimens were then kept in a conditioning room for 24 hours prior testing. All the specimens were tested at a crosshead speed of 2.5 mm/min in order to ensure that the failure of the tested specimens occurred between 30 and 120 seconds. The IB strength was calculated based on the Eq. (4).

$$IB\ (MPa) = \frac{P}{A} \tag{4}$$

where P is the maximum load applied on the tested specimen (N), A is the cross-sectional area of the specimen (mm^2).

Dimensional stability

The same specimens were used for determination of both water absorption and thickness swelling simultaneously. The dimensions of the specimens were (100 × 100 mm). Each specimen was tested in ten replicates. For the thickness swelling test, a permanent line was drawn approximately 25 mm from one edge, and, later, three cross marks were made along that line at distances of 25, 50 and 75 mm. Each test specimen was immersed in fresh clean water at ambient temperature, and arranged in a vertical position to ensure that all specimens were covered by approximately 15 mm of water. The edges of each test specimen were separated by a distance of at least 10 mm from one another, and from the bottom of the container. Readings were taken at each 2 hours until a total of 106 hours soaking, and then each test specimen was withdrawn from the water, wiped with a damp cloth and weighed. The water absorption of the test specimen was calculated using the Eq. (5).

$$WA\ (\%) = \frac{(M_2 - M_1)}{m_1} \times 100 \tag{5}$$

where, m_1 = weight of the tested specimen before immersion (g), m_2= weight of the tested specimen after immersion for 2 and 24 hours (g); the thickness of each tested specimen was re-measured at the same cross marks. The thickness swelling of the tested specimen was calculated based on the Eq. (6).

$$TS\ (\%) = \frac{(t_2 - t_1)}{t_1} \tag{6}$$

where, t_1 = mean thickness of the tested specimen before immersion in water, t_2= mean thickness of the tested specimen after immersion.

2.2.3. Statistical analysis

The data were statistically analysed using Statistical Analysis System (SAS) software. Analysis of Variance (ANOVA) was used to examine the effect of board density on properties of CBKCB. Least Significant Difference (LSD) method was used for further evaluation of the effect of board density. LSD ranks the means and calculates the minimum value to be significantly different with each other at $p \leq 0.05$. Means followed by the same letter are not significantly different.

3. Results and Discussion

3.1. Fibres size distribution

Kenaf bast fibres produced in this study were evaluated based on fibre size distribution, an average width/thickness and length of the fibres. The results revealed that more than 70% of the KBFs were retained in a sieve having a pore size of >3.35 mm (Fig. 1). The average thickness and length of approximately 100 pieces of KBFs taken randomly from each replicate were 0.075±0.005 mm and 31±0.4 mm, respectively. Normally, fibres with high length: thickness ratios are more preferred for production of wood cement composites because the long fibres would give a higher aspect ratio, and, hence, provide a larger contact area between the fibres and cement, thus resulting in a better bonding. Generally, the results of current study show that the KBFs are thinner and longer than wood fibres [17]. These results correlate with the findings of previous work on kenaf core and bast fibres which stated that kenaf bast fibres were thinner and longer [17].

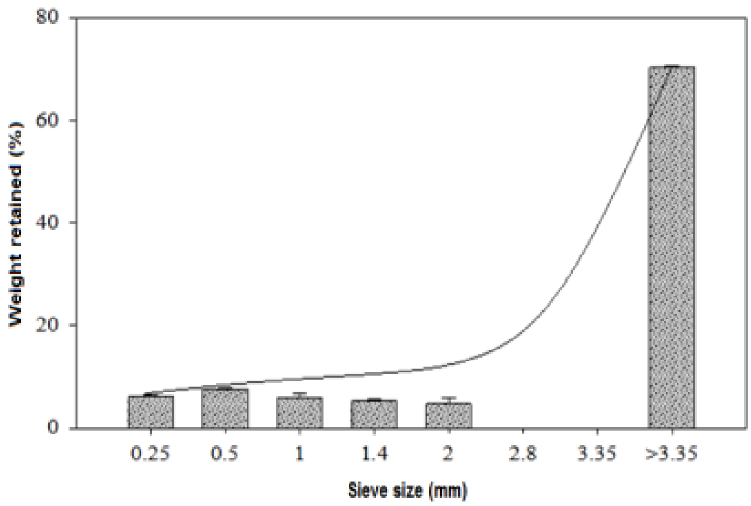


Fig. 1. Fibres size distribution of kenaf bast fibres obtained after cutting process (Fibre cutter Model Ireson Engineering).

3.2. Effect of board density (BD) on the mechanical properties of CBKCBs

The average board density observed in this study was in the range of 1,093-1,435 (kg/m^3) while the moisture content (MC) ranged from 10% to 12%. The statistical analyses were carried out using the corrected values (Table 1). It is clear that density is significantly affect the strength (MOR and MOE) and dimensional stability (WA and TS) of the boards. All the values obtained in this study were adjusted to board densities of 1100, 1300 and 1500 kg/m^3 and MC of 12%.

Table 1. Summary of ANOVA of the effect of board density (BD) on MOR, MOE, IB, WA and TS of the CBKCBs.

Source	DF	P value						
		MOR	MOE	IB	WA2h	WA24h	TS2h	TS24h
Board density	2	<.0001 ***	0.0005 ***	<.0001 ***	<0.0001 ***	0.0001***	0.0624*	0.0010***

*** and * indicates significant difference at p<0.01 and p<0.1, respectively.

The effect of the board density on MOR, MOE, IB, WA and TS of CBKCBs were found to be significant (P<0.01 and 0.1). Generally, the presence of KBFs in CBKCBs significantly reduced their MOE and IB, irrespective of the board density. The best MOR was observed with board density 1100 kg/m^3 (Table 2).

Table 2. Effect of board density on the mechanical properties of the CBKCB[a].

Cement: KBF/ratio	board Density (kg/m^3)	Mechanical properties (MPa)[b]		
		MOR	MOE	IB
2:1	1100	6.04a (0.75)	1918a (362.9)	0.031a (0.009)
	1300	4.12b (0.88)	1420b (275.2)	0.012b (0.005)
	1500	4.84b (0.77)	1375b (239.5)	0.012b (0.008)
MS 934, 1986		>9.0	>3000	>0.5

[a]Values are average of 10 specimens; ( ) standard deviation.
[b]Means followed by the same letters (a, b) in each column are not significantly different at P ≤0.05 according to Least Significant Difference (LSD) method.

The range of board density used in this study (1100-1500 kg/m^3) had a little influence on any of the strength properties, particularly in CBKCBs. The boards made at a density of 1100 kg/m3, have showed significantly high strength (Fig. 3a). Conversely, stiffness of the boards was found to be significantly reduced by increasing the board density (Fig. 3b). The IB was also reduced tremendously, suggesting lack of or very limited bonding (Fig. 3c). Apparently, this lack of bonding is caused by uneven distribution of fibres in the board creating lumps which are clearly seen on the surfaces of the boards (Fig. 2). This observation might be due to the fact that density of the kenaf bast fibres is less than half that of cement, therefore, increasing the board density will increase the fibre quantity, thus the heavy cement particles will concentrate into the middle of the board and surrounded by the fibres on both sides of the board. Furthermore, insufficient amount of cement required to cover the large quantity of KBF was another main reason for this poor bonding

On the other hand, the decrease in MOR with increasing density observed in our results contradicts the fact that MOR increases with density. This could be attributed to the fact that in our samples with higher density (more fibre), the fibres are aggregates with different shapes rather than individual fibres and are not uniformly distributed within the board (Fig. 2). Thus, it is expected that the measurements taken at regions concentrated with aggregated fibres will lead to low values of MOR and MOE, Figs. 3(a) and 3(b).

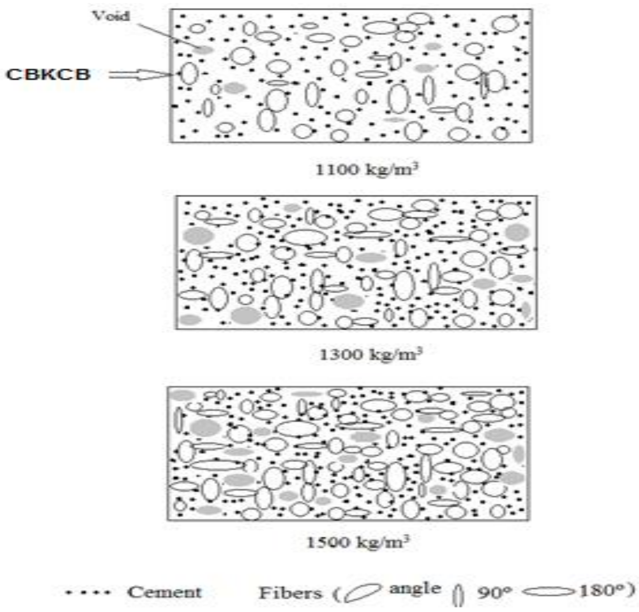
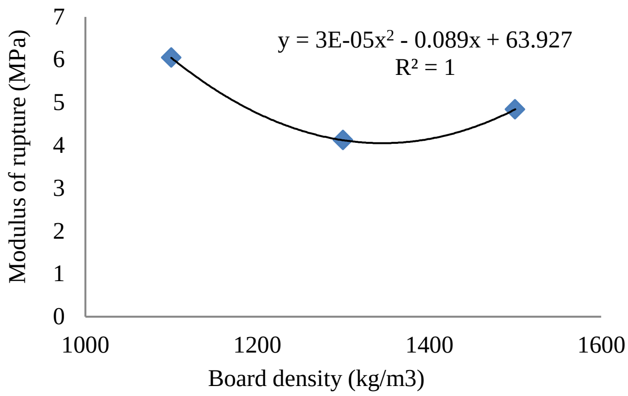
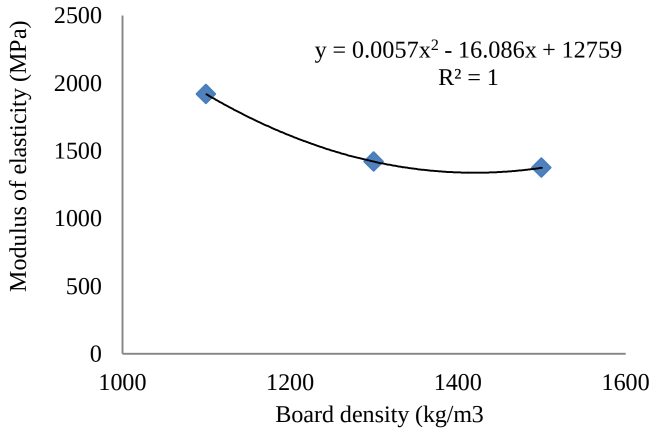


Fig. 2. Schematic observation of distribution of cement aggregates and KBFs in the CBKCB.

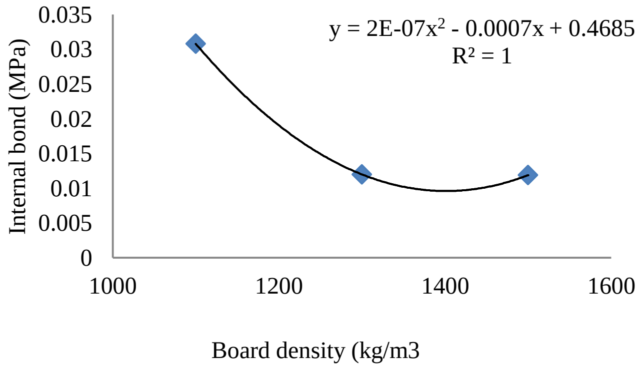
Also, the surface of the CBCKB was observed from two view angles, namely, through a clean cross cut view of the CBKCB, as shown in Fig. 4. The surface appearance of the CBKCB, observed from one edge of the board is shown in Fig. 5. It shows that, generally, the kenaf bast fibres are randomly distributed within the boards. It has been observed that board density of 1100 kg/m3 shows the best homogeneity of the cement and fibre mixture, however, some aggregates also exist. On the other hand, there was a clear separation between the fibre and cement, which is represented by three layers in both 1300 and 1500 kg/m3 densities indicating poor homogeneity. The results of this work are in accordance with those of the study stated that with increase in wood volume in the board, the stress concentration around the component particles are more diffused, thus resulting in an increased applied stress [18]. It was also previously reported that increasing wood content up to 60% yielded a reduction in the bending strength [19]. Therefore, 1100 kg/m^3 was considered the most suitable.



(a) Modulus of rupture (MOR)



(b) Modulus of elasticity (MOE)



(c) Internal bond (IB) of the CBKCBs

Fig. 3. Effect of board density (BD).

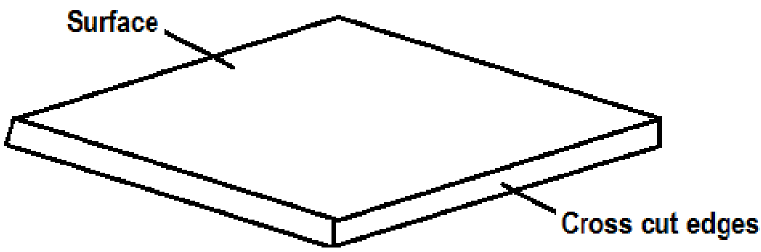


Fig. 4. Diagram of CBKCB showing area of observation under stereo microscope.

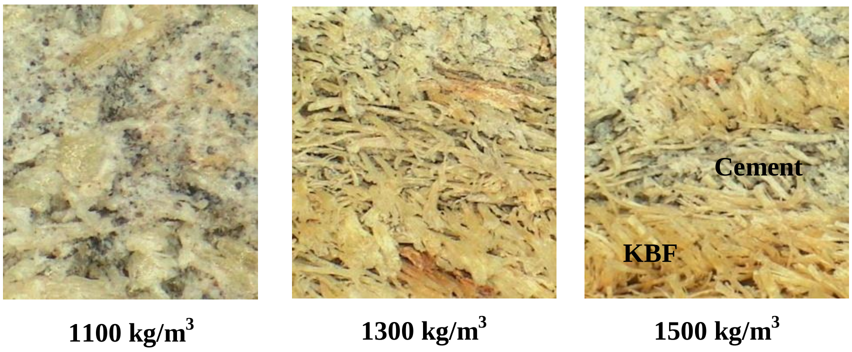


Fig. 5. Cross cut view of CBKCB with different densities.

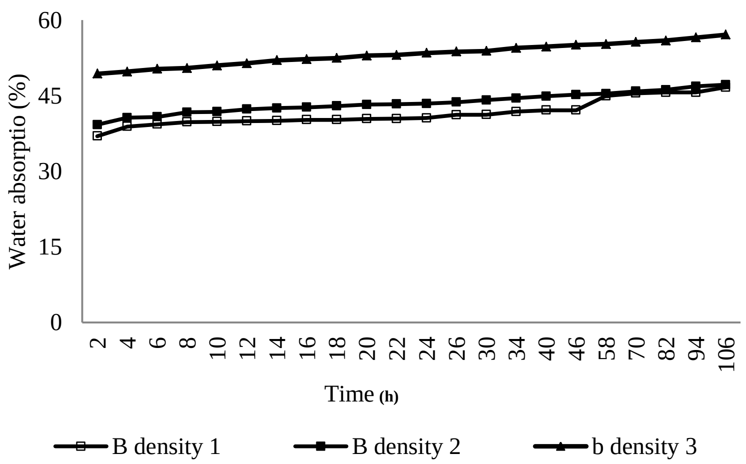


Fig. 6. Water absorption profiles of 2:1 (cement: KBFs) CBKCBs with different densities (1) 1100 (2) 1300 and (3) 1500 kg/m^3.

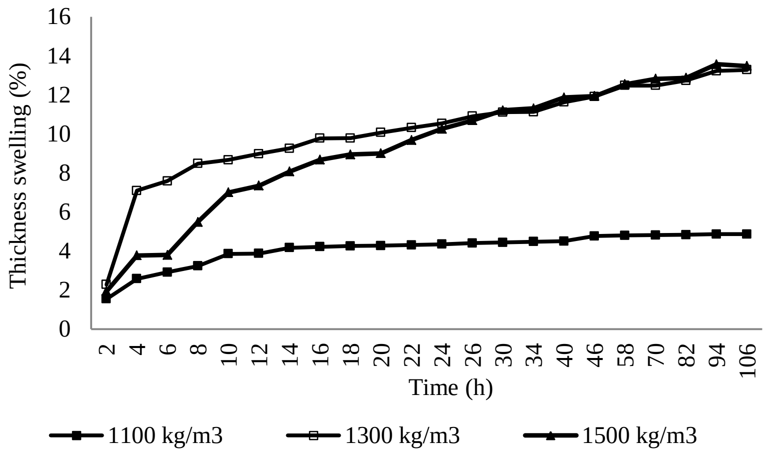


Fig. 7. Thickness swelling profiles of 2:1(cement: KBFs) CBCKBs with different densities (1100, 1300 and 1500 kg/m^3).

3.3. Effect of board density (BD) on the dimensional stability of CBKCBs

Due to the dimensional instability of KBFs, the water absorption (WA) and thickness swelling (TS) have been investigated for a duration of up to 106 h until reaching their maximum saturation (Figs. 6 and 7). From Fig. 6 it is obvious that there was a small increase in WA with increasing the board density, while, the TS was noticeably increased from 4.86% with board density 1100 kg/m^3 to 13.47% with the board densities of 1300 and 1500 kg/m^3 (Fig. 7).

From the figures, it can be clearly seen that after 24 h there was no remarkable increase in WA and TS; therefore, the maximum time was limited to 24h (Table 3).

Table 3. Effect of board density on the dimensional stability of CBKCBs[a].

Cement: KBFs ratio	board Density (kg/m^3)	dimensional stability[b] WA 2h	WA 24h	TS2h	TS24h
2:1	1100	36.98c (0.62)	40.55b (0.017)	1.54b (0.38)	4.38b (0.23)
	1300	39.23b (1.78)	43.43b (2.50)	2.28 a (0.52)	10.53a (1.25)
	1500	49.36a (0.43)	53.49a (1.12)	1.93ab (0.039)	10.69a (1.67)
MS 934 (1986)		na[2]	na[2]	<2.00	<2.00

[a] Values are average of 10 specimens; ( ) standard deviation.
[b] Means followed by the same letters in each dimensional stability columns are not significantly different at $p < 0.05$; [2]na=not available.

The observed increase in both WA and TS associated with the increase in board density could be attributed to the large quantity of fibres used. Because of the hygroscopic property of KBFs, the fibres absorb water through their cell walls filling up the voids until reaching their saturation. Thus, samples with the greatest fibre quantities will have the greatest WA and TS. It was reported that hydrogen bonding can also be formed between water molecules and the free hydroxyl groups found on the cellulosic cell wall, thus enhancing water diffusion into the specimen [20]. Moreover, penetration of water by the capillary action also increases the number of porous tubular structures in the specimen. After saturation of the cell wall, the water occupies micro void spaces [20]. Similar effects were also previously noticed and reported by other researchers [21-22]. The WA values observed in this research are in accordance with the previous findings reported on rattan cement composite [23-25] and other composites based on agricultural and forestry residues, such as maize, coconut husk, stalk and coffee husk [26-27].

4. Conclusions

From the findings of this study it could be concluded that the most suitable board density for CBKCB was found to be 1100 kg/m3as it produces the highest values of (MOR), stiffness (MOE) and IB. The board density enhances both WA and TS.

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