Journal of Engineering Science and Technology
Vol. 15, No. 2 (2020) 1124 - 1138

EFFECTS OF KENAF BAST FIBRE AND SILICA FUME CONTENT ON BENDING STRENGTH AND DIMENSIONAL STABILITY OF CEMENT BONDED KENAF COMPOSITE BOARDS

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Abstract

The objective of this study is to evaluate the effect of silica fume concentrations on the hydration properties of cement-kenaf fibres mixtures. Also, to examine the effect of the proportions of kenaf bast fibres and the presence of silica fume on the mechanical properties and dimensional stability of cement-bonded kenaf composite boards (CBKCB). The CBKCB were manufactured using 2:1, 2.5:1 and 3:1 (w/w) cement: kenaf bast fibre (KBF) proportions, and 0, 5, 7 and 10% silica fume (SF) concentrations. Modulus of rupture (MOR), modulus of elasticity (MOE), internal bond (IB), water absorption (WA), and thickness swelling (TS) of the CBKCBs were investigated. The KBF was found to be compatible with cement. With regard to effect of cement: KBF proportions, the order of both MOR and MOE was 2:1 > 2.5:1 > 3:1 while order of the IB was 3:1 > 2.5:1 > 2:1. Adding 7% of SF improved the IB by 83% at 2:1 proportion. The best combination for the production of acceptable performance CBKCB is by using decorticated KBF, at 2:1 (cement: KBF) and 7% SF. The properties of MOR (10.9 MPa), MOE (5061 MPa), IB (0.15 MPa), and WA (23.7 and 27%), TS (0.87 and 3.01%), after 2h and 24h respectively) were reported. Thus, CBKCB is considered to be a promising material for different structural applications.

Keywords: Kenaf fibre, Mechanical properties, Physical properties, Silica fume.

1. Introduction

The application of plant fibres in the manufacture of composite materials has received great attention from both researchers and industrial sector [1]. Natural fibres are lignocelluloses materials that are cheap and readily available in huge quantities in most tropical and subtropical countries [2]. Interestingly, natural fibres are biodegradable and have excellent mechanical properties (e.g., tensile strength) compared to synthetic fibres [3]. The current global production of these natural fibres is estimated at approximately 30 million tons per year, which is mainly concentrated in Asian countries [1]. During the past few decades, more interest has been given to the application of natural fibres as a reinforcement agent in cementitious materials especially for construction applications [4-6]. The investigations revealed that the natural fibres reinforced cement products not only satisfy the required specifications on strength, but they also provide other advantages such as renewability, good insulating properties and low energy consumption [7-10].

Some previous works have reported that fibres from non-wood resource were found to be suitable and have been widely used in the production of cement-based composites [11-13]. Among these fibres, coir, coconut husk, sisal, corn stalk, hemp, flax, eucalyptus, and pineapple leaf fibres were used to reinforce cement to produce low-cost building materials [14, 15]. It was also reported that mortar containing these admixtures are already used for insulation or coating applications. The main disadvantages of these composites are their sensitivity to the environmental conditions as well as their dimensional instability [16].

Recently, the use of fibre-reinforced cement as a building material has increased rapidly, especially in developing countries, which have invested heavily in this technology [10]. Most of the recently conducted researches regarding cement-bonded wood composites were focused on cement-bonded particleboards [17, 18], the compatibility of wood and non-wood species with cement [19], the decay resistance [20] and the dimensional instability [21].

Silica fume (SF) has also been extensively used in cement boards to improve the strength [17]. The selectivity of SF was due to easiness of its application, its low cost and ability to improve the cohesive strength of the fresh composite [17, 22]. Silica fume is a by-product during the process of manufacture of ferrosilicon alloys and silicon metal as a result of the reduction of highly pure quartz with coal carried out in the electric arc furnace [23]. It has been stated that in some cases, the presence of cement particles can reduce the positive effect of SF on the microstructure and mechanical properties of the pastes [24, 25]. The presence of silica fume agglomerates can result in a matrix expansion due to the alkali-silica reactions that can take place [26]. Due to these advantages, the SF was selected as the most well-known additive material for the production of high strength concrete during recent years [27].

Kenaf bast fibres (KBF) are natural fibres obtained from the kenaf stem. However, numerous researches have been conducted on natural fibres-based composites; there has been a very limited published research on the utilization of KBF in cement composites. Therefore, the purpose of this research is to investigate the potential of KBF as a reinforcing agent for the production of cement-bonded boards. The research also evaluates the influences of different SF concentrations (0, 5, 7, and 10%) on the properties of kenaf bast fibre-cement-water mixtures, as well as the effect of cement: kenaf proportions on the MOR, MOE, IB, WA and TS of the CBKCB.

2. Materials and Methods

2.1. Materials

The kenaf bast fibres (KBF) used in this study were obtained from a local farm in Taman Pertanian Universiti (TPU) Malaysia, ordinary Portland cement type II used as an inorganic binder was obtained from NS Cement Industries Sdn. Bhd. Malaysia and silica fume type MBT MB-SF was obtained from BASF Sdn. Bhd. Malaysia. The research was carried out at the Forest Research Institute Malaysia (FRIM), Kepong, Malaysia.

2.2. Methods

Separation of the kenaf bast fibres from the stem was carried out using a locally fabricated decorticating machine (Fig. 1).

Fig. 1. A decorticating machine.

The KBF was air room temperature for two weeks to attain moisture content (MC) of approximately 12% prior to their use. The decorticated KBF was further cut into short fibres using a fibre cutter (Model Ireson Engineering) and were further segregated by size using a vibrating screen. The fibres retained over >3.35 mm sieve was selected to be used in this research since they represent >70% of the screened KBFs. According to Rahim [28], firstly, in order to determine the kenaf-cement compatibility and the effect of SF concentrations on the hydration rate, the hydration test was carried out using the hydration test machine. This test was carried out based on mixing the formulation stipulated in the recognized method of ASTM C 186-83 (1983). The ratio of water/cement was 0.4 (ml/g) while for water/wood was 0.7 (ml/g). The mixing process was carried out inappropriate polyethylene bags to reduce the transfer time and possible material loss during transfer. A thermocouple Type J wire was inserted into each mixture before placing the mixture in a

thermo flask. Any temperature rise from these mixtures was recorded automatically by the hydration test machine until overnight.

The cement-bonded kenaf composite boards (CBKCB) were produced using (2:1, 2.5:1 and 3:1) cement: KBF proportions and (0, 5, 7 and 10%) SF concentrations, based on the cement weight. The board density was 1100 kg/m3. For each combination, six boards were fabricated. The CBKCB production was performed as follows; firstly, the cement and SF were thoroughly mixed together in a container. Secondly, the KBF was placed into a mixer and water added while the mixer was rotating. Finally, the prepared mixture of the cement and SF was added to the wetted KBF into the mixer. Based on studies by Rahim et al. [29], the amount of water used was computed as shown below in Eq. (1):

$$Wt = 0.35C + (0.030 - MC)W \quad (1)$$

where: Wt = weight of water (g), W = dry weight of KBF (g), MC = the moisture content (%), and C = weight of the cement (g).

The boards were produced by inserting the prepared mixtures into wooden moulds of 450 mm × 450 mm × 12mm dimensions placed on a metal plate covered with a polyethylene sheet. Each formed board was then covered with another polyethylene sheet and a metal plate on the top. Several boards were produced at once, then clamped together and pressed at 480 kg/m^3 for 24 hours using a cold hydraulic press. After 24 hours the clamps were released, the metal plates and polyethylene sheets were removed, and the CBKCBs were stacked vertically in the water-saturated chamber and kept for 7 days at a temperature of 20±1ºC and 90±5% relative humidity (RH) to allow the curing of cement and to gain strength. Then the boards were conditioned at ambient room temperature (23±1ºC and 80±5% RH) for 21 days to reach the MC of 12%. It was noticed that a long pressing time is necessary due to the very slow hydration process of the ordinary Portland cement. Typically, the hydration process takes at least 8 hours in the early stage (setting) where the reaction releases a considerable heat, while the second stage (hardening) is estimated to be completed in 28 days.

The produced boards were first trimmed to avoid edge effects on the tested specimens. The trimmed boards were further cut into different sized samples specified for each test and stored in a laboratory chamber at a temperature of 27±2ºC and 65±5% relative humidity for 5 days prior to their testing. Both mechanical properties and dimensional stability of all fabricated CBKCB were performed according to the MS 934:1986. The tests were carried out by using an Instron Testing Machine (Model 4204). Replicate samples of 225 mm × 100 mm dimensions were used to determine the MOR and MOE using an Instron Testing Machine (Model 4204). Each test specimen was supported horizontally on parallel metal rollers having a diameter of 20-25 mm and centre-to-centre spacing of 200 mm. A load was then applied at the centre of the test specimen until the maximum load was reached. The crosshead speed of the load was set at 3 mm/min so that failure occurred between 30 and 120 seconds. The modulus of rupture (MOR) was calculated according to Eq. (2):

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

where, P = maximum load for the test specimen (N), L = span between centres of support (mm), b = mean width of the test specimen (mm), d = mean thickness of the test specimen (mm).

The calculation of the modulus of elasticity (MOE) was made according to Eq. (3):

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

where, *L*, *b*, and *d* stand for span, width and thickness of specimen, respectively as mentioned in Eq. (1), ΔP = increment in load (*N*), ΔW = increment in deflection (mm) corresponding to ΔP

The IB was investigated using replicate samples of 40 mm × 40 mm dimensions. Each test specimen was glued on both surfaces then sandwiched between two metal blocks. The specimens were first kept in a conditioning room for 24 hours then tested at a crosshead speed of 2.5 mm/min in order to ensure that the failure of the test specimens occurred between 30 and 120 seconds. The IB strength was calculated based on the formula in Eq. (4):

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

where; *P* = maximum applied load for test specimen (N), *A* = cross-sectional area of the test specimen (mm^2).

Water absorption (WA) and thickness swelling (TS) were investigated using replicate samples of 100 mm × 100 mm dimensions. 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. The test specimens were arranged vertically and immersed in fresh clean water at ambient temperature so 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 2 hours intervals until 106 hours of soaking. Then each test specimen was withdrawn from the water, wiped with a damp cloth and weighed accurately. Water absorption of the tested specimens was calculated using Eq. (5).

$$WA\ (\%) = \frac{(m_2 - m_1)}{m_1} \times 100 \quad (5)$$

where, m_1 = weight of the test specimen before immersion (g), m_2= weight of the test specimen after immersion for 2 and 24 hours (g).

The thickness of each test specimen was re-measured at the same cross marks with a suitable apparatus to an accuracy of ± 0.05 mm. Then the thickness swelling of each tested specimen was calculated based on the Eq. (6):

$$TS\ (\%) = \frac{(t_2 - t_1)}{t_1} \times 100 \quad (6)$$

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

3. Statistical Analysis

Analysis of Variance (ANOVA) was employed to determine the effect of different process variables on the board's properties, while the Least Significant Difference (LSD) was used to determine the level of significant differences between samples means.

4. Results and Discussion

4.1. Effect of SF concentrations on the hydration properties

The effect of SF concentrations on the hydration properties is displayed in Fig. 2. Results of the hydration characteristics showed that the pure cement as control has attained a maximum hydration temperature (MHT) of > 80 ºC within 8 hours. In a presence of 0%, 5%, 7% and 10% SF (w/w cement), the MHT was reduced to 64.1 ºC, 64.7 ºC, 67.8 ºC and 63.3 ºC, respectively.

However, in all SF concentrations, the time required to reach MHT was not significantly affected as it remained between 6-8 hours indicating reactivity between the SF and cement. Sandermann et al. [30] mentioned that three different categories for compatibility between wood species and cement have been previously classified before any wood fibre is considered for use in the wood cement composite manufacture.

The authors classified the wood cement admixtures, which recorded MHT of $\geqslant$ 60 ºC, 50-60 ºC, and $\leqslant$ 50 ºC as compatible, intermediate, and incompatible, respectively. Based on this classification, the KBF is classified as compatible with Portland cement.

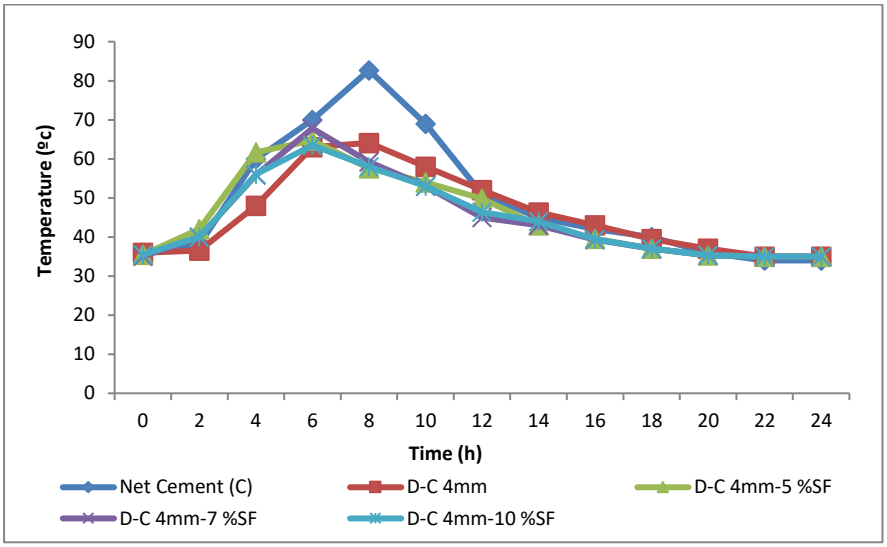

Fig. 2. Effects of silica fume concentrations (0, 5%, 7% and 10%) on the hydration process of Portland cement.

4.2. Effect of cement: KBF proportions and SF concentrations on the properties of CBKCB

Table 1 shows the effects of the main factors namely cement: KBF proportions and SF concentrations as well as their interactions on the mechanical properties and dimensional stability of CBKCB. From Table 1, in general effects of the main factors and their interactions on the properties of CBKCB are highly significant ($P<0.01$ and 0.05).

Table 1. Summary of ANOVA on the mechanical properties and dimensional stability of CBKCB.

Source	DF	P value				
		MOR	MOE	IB	WA	TS
Proportions	2	< 0.0001***	< 0.0001***	0.0002***	< 0.0001***	< 0.0001***
SF concentrations	3	< 0.0001***	< 0.0001***	0.0002***	< 0.0001***	< 0.0001***
Proportions × SF concentrations	6	< 0.0001***	< 0.0001***	< 0.0001***	< 0.0001***	0.0871*

*** and *indicates significant difference at $p < 0.01$ and $p < 0.05$

Generally, the flexural behaviour and internal bonding of CBKCB for all cement: KBF proportions were investigated. As shown in Table 2 adding fibres changes in the maximum flexural strength. The maximum MOR for cement: KBF proportion 2:1, 2.5:1 and 3:1 was 6.04, 4.46 and 3.64 MPa, respectively (Table 2). It is clearly seen that the highest MOR and MOE were found with 2:1 (cement: KBF proportion) followed by 2.5:1 and 3:1. As can be seen, adding 25-29 % fibres enhanced the MOR by 33 %. However, this addition reduced the MOR and MOE by 65.9-35.4 % and 106.7-24.9 %, respectively.

After analysing the broken tested specimens, it was observed that some parts of KBF were not uniformly distributed in the matrix and a significant quantity of these fibres lumped together in some parts of the board, while other parts of the board did not contain any fibre. When the amount of the fibres reached 33%, the fibres covered the whole board; however, the balling effect was still observed in some parts of the board. This means, that a minimum amount of the fibres has been distributed throughout the whole board.

The findings of this study correlate with what was reported by Khorami and Ganjian [14] who used bagasse, wheat and eucalyptus fibres as reinforcement material in cement-bonded board and found that increasing fibre content from 2 % to 4 % of cement weight, increases the maximum flexural strength. On the other hand, the greatest IB was observed with 3:1 followed by 2.5:1 and 2:1. However, 2:1 showed high MOR and MOE, its IB was very low. This is mainly attributed to the separation of fibres from cement during board formation and pressing. These phenomena created a weak inter-particle bonding among the fibres. Almost all the failures were observed at the fibre instead of the cement. With regard to 3:1cement: fibres specimens, the increase in cement was found to be associated with an increase in the IB. Increasing the cement enhances the IB in the order of 2:1 < 2.5:1 < 3:1, at the same time, both the MOR and MOE decrease. Furthermore, increasing the cement has led to an increase in board weight; therefore, 2:1 is considered the most suitable one.

Table 2. Effect of cement: KBF/proportions on MOR, MOE and IB of different CBKCB.

Cement: kenaf/proportions	Kenaf (w/w) %	Mechanical properties (MPa) 1		
		MOR	MOE	IB
2:1	33	6.04 a	1918 a	0.030 b
2.5:1	29	4.46 b	1536 b	0.044 b
3:1	25	3.64 c	928 c	0.111 a
MS 934, 1986		> 9.0	> 3000	> 0.5

Note: 1Means followed by the same letters (*a, b, c*) in each column are not significantly different at $P \leqslant 0.05$ according to Least Significant Difference (LSD) method

Generally, the addition of SF shows the different effect on cement-KBF proportion. From observation, both 7 and 10% SF improved the MOR, MOE and IB of the proportion 2:1, the best values were observed with 7% SF, which are 10.9, 5.61 and 0.15 (MPa), respectively (Figs. 3 to 5). Conversely, 5% SF increased both MOR and MOE of the proportions 2.5:1 and 3:1 and the recorded MOR values were 9.9 and 5.1 (MPa), and those for MOE were 2869, 2223 (MPa) for the proportions 2.5:1 and 3:1, respectively (Figs. 3 and 4). The SF concentrations have some positive effect on the IB of the 2:1 proportion only where the maximum value of 0.15 MPa was found with 7% SF (Fig. 5). Despite the fact that IB increased with SF concentration in 2:1 proportion, contrary it was decreased with SF in both 2.5:1 and 3:1 proportion with an exception at 10% SF in 2.5:1 proportion where the value was increased to 0.05 MPa (Fig. 5).

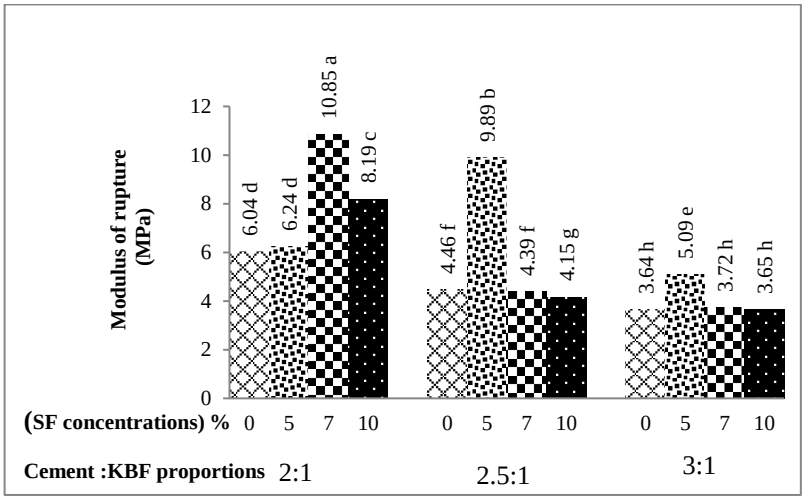

Fig. 3. Effect of silica fume concentrations (0, 5, 7, and 10) %on the Modulus of Rupture (MOR) of CBKCB with different cement: KBF proportions (2:1, 2.5:1, 3:1).

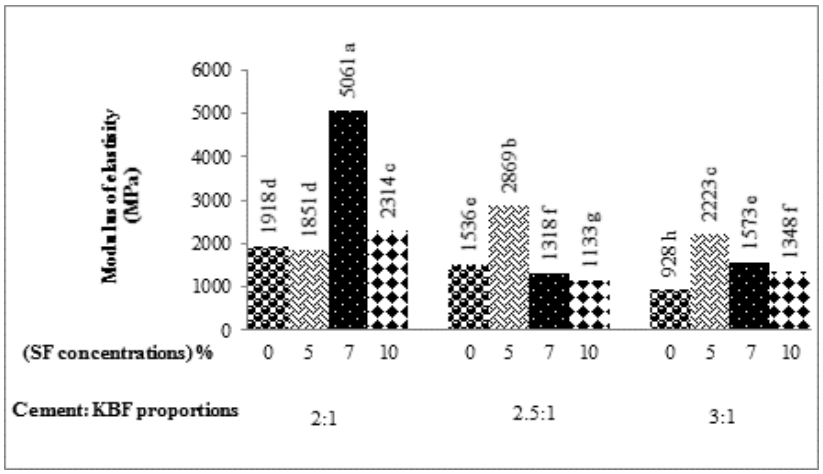

Fig. 4. Effect of silica fume concentrations (0, 5, 7, and 10) % on the Modulus of Elasticity (MOE) of CBKCB with different cement: KBF proportions (2:1, 2.5:1, 3:1).

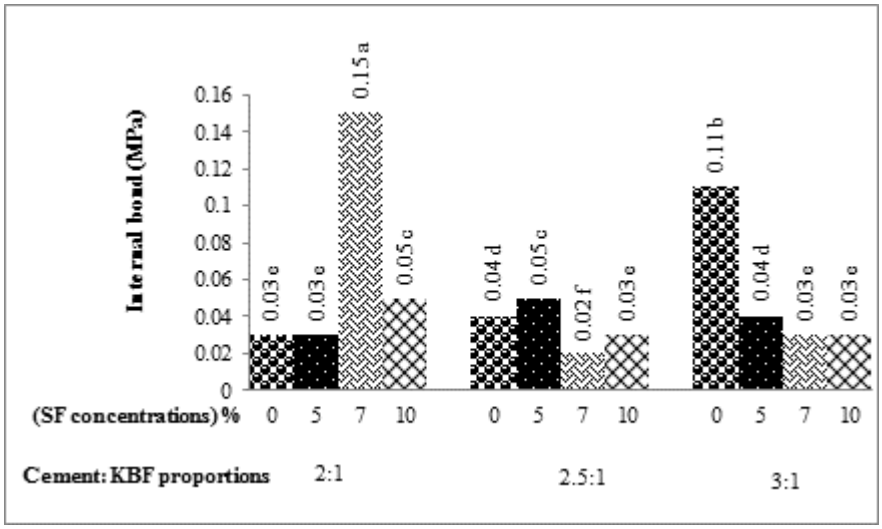

Fig. 5. Effect of silica fume concentrations (0, 5, 7, and 10) %on the Internal Bond (IB) of CBKCB with different cement: KBF proportions (2:1, 2.5:1, 3:1).

This increase in IB can be attributed to the extremely small SF particles (approximately two times smaller) compared to cement particles. The SF particles act as filling material distributed within the cement matrix, thus, reducing the porosity of the composite by filling the voids containing air and moisture (Fig. 6).

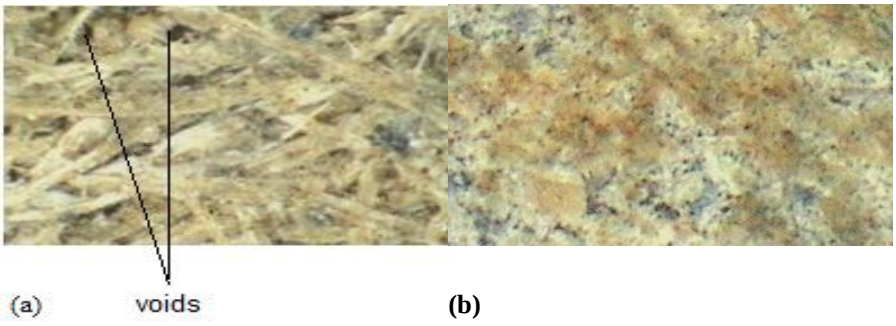

Fig. 6. Images show surface of cement-bonded kenaf composite board: (a) Without SF and (b) With SF examined under 60× magnification.

Another reason could also be due to the Pozzolanic reaction of SF leading to the formation of calcium silicate hydrate, which aids in improving the strength. Application of SF in cement composite boards reinforced by cellulose fibres increases the flexural strength because these very fine Pozzolanic materials decrease the alkaline environment of cement matrix [31]. The SF particles block the pores by tightening and strengthening the aggregate interface region, and therefore, they cause an increase in the late strength [31-33]. The use of SF was previously approved to improve the strength and durability of the concrete [34-36].

Generally, it is obvious that with increasing time the difference in WA within the different cement: KBF proportion of 2:1, 2.5:1 and 3:1 was small. Except 2:1, all other proportions reached their maximum WA after 24 hours and the highest WA (41 %) was observed with 2:1. This could be explained by the considerable quantity of fibre in the board that absorbs plenty of water (Fig. 7).

On the other hand, the TS for cement: KBF proportions were in the order 3:1 > 2.5:1 > 2:1 (Fig. 8). However, both 3:1 and 2.5:1 proportion have less quantity of fibre but they showed great WA and TS. This may be due to the voids observed in the board confirmed by the stereomicroscope picture, as shown in Fig. 6. According to Amel et al. [37], this enhanced WA and TS, associated with the cement: KBF proportion could also be attributed to the same reason explained by the board density.

From Figs. 7 and 8, it is noticeable that addition of SF to the different proportions (2:1, 2.5:1 and 3:1) decreases both WA and TS of the CBKCB and the best results were reported with 7% SF. The fastest rate of TS was observed between 6-10 hours. Generally, the WA values of CBKCB with SF were lower than those of control boards (without SF).

Large quantities of exposed KBF and free internal spaces (voids) could be the possible cause for the high WA observed in this study and consequently, the high TS. This observation could be attributed to the hygroscopic nature of the KBF. Similar observations regarding the effect of hygroscopic nature of the lignocellulosic fibres on WA and TS were also previously reported by Olorunnisola [38], Ashori et al. [39] and Davies and Davies [40]. Although, the CBKCB are dimensionally unstable; the presence of SF reduced their WA and TS. Thus, our results well correlate with what was previously reported, claiming that SF particles fill the pores in the cement-kenaf matrix, thus reducing the water absorption by the board [21, 41]. The authors stated that for wood cement boards the water absorbs primarily by the cell walls of the wood and then by the colloidal spaces of the cement paste.

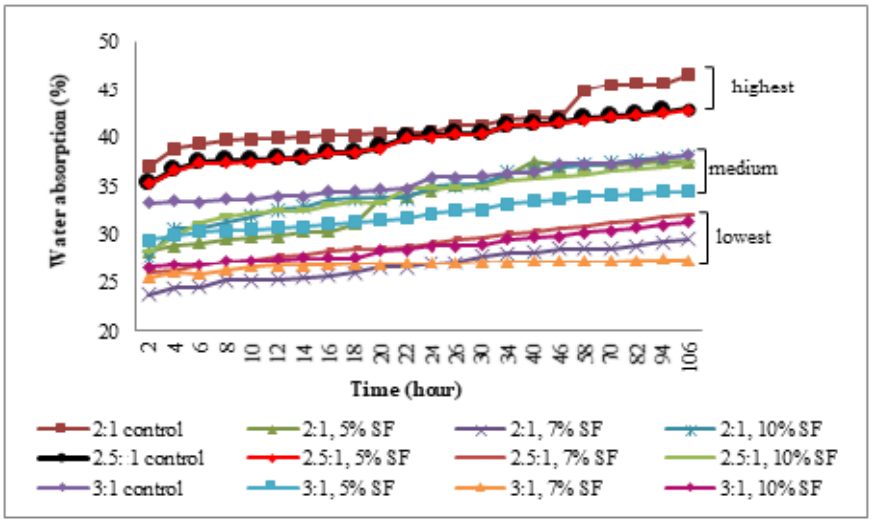

Fig. 7. Water absorption properties of different proportions of CBKCB with the presence of silica fume.

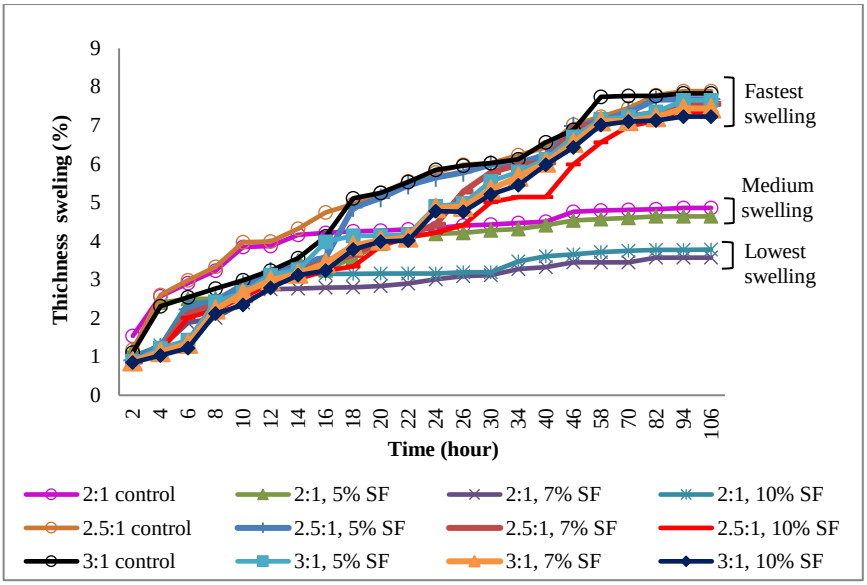

Fig. 8. Thickness swelling properties of different proportions of CBKCB with the presence of silica fume.

5. Conclusions

The findings obtained from this study can be summarized as follows:

- The hydration test revealed that the KBF is classified as compatible with Portland cement.
- The higher content of KBF associated with a significant increase in the board strength and stiffness. The highest MOR was observed with 2:1 (33% fibre content) followed by 2.5:1 and 3:1 proportion.
- Addition of different concentrations of silica fume (0, 5, 7 and 10%) in the CBKCB has positively affected the mechanical properties and dimensional stability of the CBKCB.
- Using the optimal 2:1 proportion and 7% SF yielded CBKCB having adequate strength, stiffness and 5 times increased IB.

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
ASTM	American Society for Testing and Materials
BS	British Standard
CBKCBs	Cement-Bonded Kenaf Composite Boards
FRIM	Forest Research Institute Malaysia
IB	Internal Bond
INTROP	Tropical Forestry and Forest Products
KBFs	Kenaf Bast Fibres
LSD	Least Significant Difference
MHT	Maximum Hydration Temperature
MOE	Modulus of Elasticity
MOR	Modulus of Rupture
MS	Malaysian Standard
RH	Relative Humidity
SAS	Statistical Analysis System
SF	Silica Fume
TPU	Taman Pertanian Universiti
TS	Thickness Swelling
WA	Water Absorption

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