Medium-density Fiberboard Made from Kenaf Bast and Core: Effects of Refining Pressure and Time on Specific Gas Permeability

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Studies concerning the production of medium-density fiberboard (MDF) with kenaf as an alternative fibrous material were carried out as an attempt to provide a sustainable and viable source for this lignocellulosic product. This work sought to evaluate the influence of fiber properties (including fiber length, width, wall thickness, and lumen diameter that affect aspect and flexibility ratios) on specific gas permeability in medium-density fiberboard (MDF) made from kenaf bast and core fibers, respectively. Results showed that MDF panels produced from kenaf core had significantly lower permeability than those produced from kenaf bast. This lower permeability was primarily related to the higher flexibility ratio of kenaf core fibers, which provided more surface connection area between fibers, resulting in higher integration among fibers. Lower ash and extractive contents of the core section also improved the efficiency of resin and the connection of fibers to each other; eventually lower permeability was observed in panels made from kenaf core. A high correlation was found between gas permeability and water absorption.

Keywords: Compression ratio; Fiber; Gas permeability; Kenaf core; Kenaf bast

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INTRODUCTION

The widespread utilization of wood has the potential to cause high rates of global deforestation that could result in negative environmental impacts (Joshi *et al.* 2004). This situation has led to the introduction of some composites with enhanced properties such as medium-density fiberboard (MDF). Composites, including MDF, are currently considered suitable engineering materials for building and construction (Zini and Scandola 2011; Ozdemir and Tutus 2013). Non-wood lignocellulosic biomass, such as kenaf and agricultural residues, has great potential for panels manufacturing, including the manufacture of medium-density fiber board (Juliana *et al.* 2012). Kenaf (*Hibiscus cannabinus* L.) is a biodegradable and environmentally friendly crop that is recognized as one of the lignocellulosic materials with the potential to replace wood in different sectors of the wood industry (Aisyah *et al.* 2013). In general, lignocellulosic material consists of cellulose, hemicelluloses, lignin, extractives, and inorganic matter. Kenaf has excellent properties for pulp and paper, MDF, and other composites because of its low density, minimal abrasion during processing, high filling levels, and high specific mechanical properties (Mossello *et al.* 2010). Kenaf stem is composed of an outer layer (bast) and a core, which are easy to separate either by chemicals and/or by enzymatic retting. The bast constitutes 25 to 40% of the stem dry weight and has a dense structure. The core is wood-like and comprises the remaining 60 to 75% of the stem. The bast and core have been determined to have greatly different properties in terms of both anatomy and the physical and chemical contents of their fibers. Research indicates that kenaf core fibers are higher in holocellulose and lignin, while kenaf bast fibers are higher in cellulose, extractives, and ash content (Abdul Khalil *et al.* 2010).

The values of ash content have been determined as 5.4% and 1.9% for bast and core fibers, respectively (Abdul Khalil *et al.* 2010). Ash content consists of various material salts, such as silicates, carbonates, oxalates and phosphates, potassium, magnesium, calcium, iron, and manganese, as well as silicon. High ash content is undesirable during the refining and recovery of cooking liquor (Rodríguez *et al.* 2008). The ash contents of core and bast are lower than most non-wood materials such as bamboo and rice straw, but higher than wood.

Extractives are the extraneous plant component present in small-to-moderate amounts that can be isolated using organic solvent or water. It is comprised of heterogeneous groups of lipophilic and hydrophilic compounds. According to Rodragueza *et al.* (2008), material with little or no extractive content is the most desirable. Both bast and core contain lower extractive contents than wood, with higher extractive content in bast than in core.

Fiber morphological characteristics play a key role in determining the suitability of any wood species or other raw material for fiberboard manufacturing (Xing *et al.* 2006). The separation of kenaf stem into bast and core may affect the commercialization of this raw material (Voulgaridis *et al.* 2000). Beating or refining the fibers is an essential process and is carried out to varying degrees. Variables such as fiber properties, equipment characteristics, and process variables also affect the refining process and final properties of the fibers.

The importance of plant materials, fiber dimensions, and their derived values on the mechanical strength of fibers has been well-documented (Azizi *et al.* 2010); all these variables affect the compactness and the composite matrix system, significantly affecting physical and mechanical properties of the produce composite panels, including permeability. Several researchers have carried out studies concerning the production of particleboards, fiberboards, and medium-density fiber board with kenaf as an alternative raw material. Permeability describes the way fluids are transferred throughout the structure of a porous solid material under a pressure gradient (Taghiyari *et al.* 2010, 2014). This physical property is extremely important to the development of durable materials, since it can be associated with their structural properties and resistance to the penetration of environmental degradation agents (Taghiyari 2013). Permeability strongly depends on the microstructure of the material, which is affected by the production and processing variables such as resin content, hot-press time and pressure, size of wood particles or fibers, de-fibration conditions (Nayeri *et al.* 2013, 2014; Taghiyari *et al.* 2010, 2014).

To our knowledge, no direct research project has so far been carried out on the relationship between permeability with water absorption and/or thickness swelling of post-pressed wood-composite panels. The present study was therefore conducted to evaluate the influence of different parts of kenaf stem (bast and core) and to evaluate the permeability and water resistance properties of the manufactured MDF. Because of the fact that many characteristics of bast differ from those of core, the question may arise as to what extent they may differ. Since permeability is one of the most important physical properties because of its impact on utilization in various industries such as wood preservation, wood drying, and permeation (Taghiyari 2013), the present study sought to determine the measurement of permeability in MDF manufactured from the stem, bast, and core of kenaf, respectively.

EXPERIMENTAL

Materials

Raw material preparation

Five-month-old kenaf (*Hibiscus cannabinus* L.) stems were obtained from the National Kenaf and Tobacco Board plantation, located in Kelantan, Malaysia. The stems were separated into bast and core, then refined using a thermo-mechanical pulping (TMP) refiner at the MDF pilot plant, located in the UKM field station at the Malaysian Palm Oil Board (MPOB), Selangor, Malaysia. The Sprout-Bauer (ANDRITZ, Austria) TMP refiner was equipped with a 300-mm diameter refiner plate with a 0.36-mm plate gap, running at varying speeds in the range of 4000 rpm. After refining, the fiber was discharged through the blow-line and dried with a flash tube dryer. No wax or resin was injected during refining. The target moisture content of the refined fibers after tube drying was about 20%. The kenaf chips were refined at three digestion pressures; 3, 5, and 7 bars for 3 and 5 min of heating time, respectively. Fibers were then dried in the oven to achieve a moisture content (MC) of 4 to 5%.

Preparation of the MDF board

The refined fibers were dried until they reached a 4% moisture content in a traditional oven before resin blending. Solid ammonium chloride (NH_4Cl) (0.1%, based on resin solid) and water were mixed into the conventional urea-formaldehyde adhesive (WC-10) with a 65% solid content. The diluted glue was sprayed onto the fibers with consistent parameters using a mechanical rotary drum blender with an internal spray nozzle. The adhesive levels were set at 12%, expressed as a percentage of adhesive solid weight based on the oven-dried fiber weight. Then, the resinated fibers were manually formed into mats using a wooden frame. All the MDF mats were hot-pressed under the same hot-pressing parameters at 175 °C for 5 min. (Xing *et al.* 2007). After being conditioned at 22 °C and 65% relative humidity for two weeks, the boards were trimmed to 300 mm × 300 mm. The manufacturing parameters are provided in Table 1.

Table 1. Lab Panel Manufacturing Parameters

Processing Parameter	Value
Nominal density (kg/m^3)	700
UF resin content (%)	12
Panel dimension (mm)	300 × 300 × 10
Catalyst content (NH_4Cl)	0.1% (solid basis on resin solid)
Press temperature (°C)	175
Total press time	300 s

Methods

Gas permeability measurement

Before gas permeability specimens were cut, MDF boards were kept in a conditioning chamber until they reached a moisture content of 10.0% (Fig. 1). In the present study, the specimens used were cylindrical, 18 mm in diameter, and because of technical reasons, 10 mm long. From each board, 8 specimens were cut randomly from scattered locations. Gas permeability was measured using the falling water displacement volume method (Taghiyari *et al.* 2010). In this method, gravity provides the necessary vacuum application (negative pressure) for the fluid, *i.e.*, air, to pass through the specimens. The value of applied negative pressure is dependent on the diameter of the water column, as well as its length. The greater the diameter and length of the water column, the greater the difference in pressure. Specimens were tightly connected to the apparatus, so that only fluid could pass through them. A pressure gauge was connected to the apparatus to monitor the pressure difference (ΔP) at any particular time and height of water column (Taghiyari and Moradi Malek 2014). Specific gas permeability was measured at three different water columns (*i.e.*, three applied negative pressures) to find out if different levels of applied vacuum may have any significant effect on the final specific gas permeability measured (Taghiyari 2013).

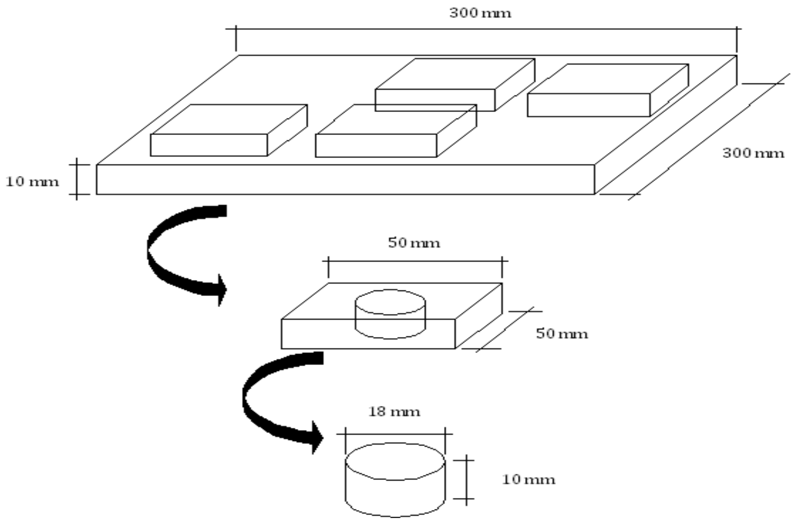


Fig. 1. Sampling scheme for the preparation of the specimens for permeability tests

Three measurements were taken for each specimen for time measurements. The superficial permeability coefficient was then calculated using Eqs. 1 and 2 (Taghiyari 2013). The superficial permeability coefficients were then multiplied by the viscosity of air (μ=1.81×10-5 Pa s) to determine the specific permeability (K=kg μ).

$$k_g = \frac{V_d CL(P_{atm} - 0.074\bar{z})}{tA(0.074\bar{z})(P_{atm} - 0.037\bar{z})} \times \frac{0.760mHg}{1.013\times10^6 Pa} \tag{1}$$

$$C = 1 + \frac{V_r(0.074\Delta z)}{V_d(P_{atm} - 0.074\bar{z})} \tag{2}$$

where k_g is the longitudinal permeability (m^3/m), V_d is $\pi\ r^2\ \Delta z$ [r=radius of measuring tube (m)] (m^3), C is the correction factor for gas expansion as a result of changes in static head and the viscosity of the water, L is the length of the wood specimen (m), P_{atm} is the atmospheric pressure (m Hg), Z is the average height of water over surface of reservoir during the period of measurement (m), t is time (s), A is the cross-sectional area of the wood specimen (m^2), Δz is the change in the height of water during time (t) (m), and V_r is the total volume of the apparatus above point 1 (including the volume of the hoses) (m^3).

Scanning electron microscopy (SEM)

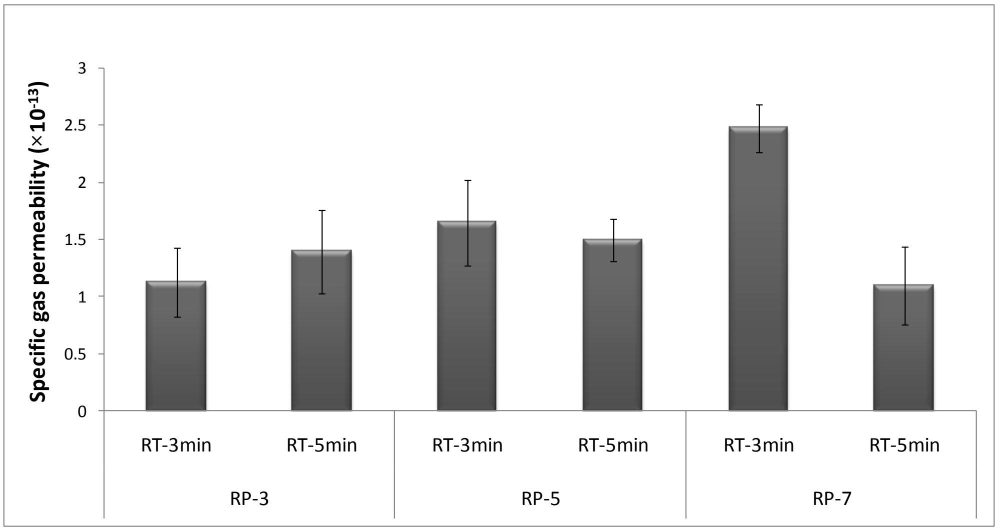
Fibers for SEM micrographs of each treatment were prepared as explained in the “raw material preparation” section. The pulped fibers were mounted onto specimen stubs, and viewed under a Philips 400 scanning electron microscope (The Netherlands) operating at an accelerating voltage of 20 kV.

Statistical analysis

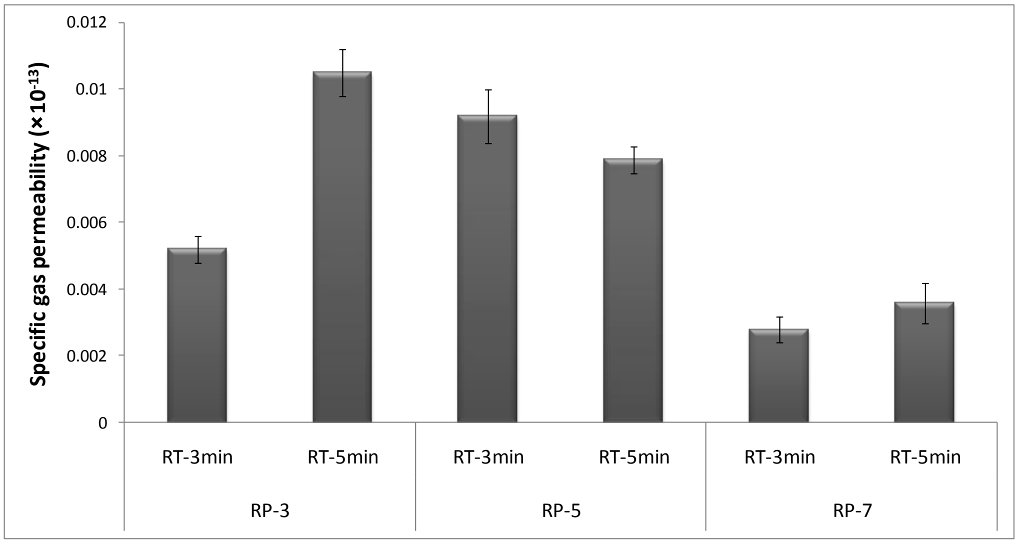
Statistical analysis was conducted using SAS software, version 9.2 (Cary, NC, USA). Two-way analysis of variance (ANOVA) was performed on the mean data to determine significant differences at the 95% level of confidence. Hierarchical cluster analysis, including dendrograms and Ward methods with squared Euclidean distance intervals, was carried out using SPSS/18, version 18 (IBM, USA). Cluster analysis was performed in order to find the similarities and dissimilarities between treatments based on more than one property simultaneously. The scaled indicator in each cluster analysis shows similarities and differences between treatments; lower-scale numbers show similarities, while higher-scale numbers show dissimilarities. Fitted-line and scatter plots were created using Minitab software, version 16.2.2 (Minitab Inc., USA).

RESULTS AND DISCUSSION

The specific gas permeability values measured for all samples based on the three different water columns (three different vacuum pressures) indicated no statistically significant difference (at 95% level of confidence), demonstrating that all three vacuum pressures can authentically be used for gas permeability measurement in MDF made from bast and core. Similar results were previously reported for other wood-composite panels, namely particleboard and medium-density fiberboard (MDF) (Taghiyari 2013; Taghiyari and Farajpour 2013). However, in some materials or under some conditions in which the resin is partly broken down and some fibers became loose, high vacuum pressure may move the loose fibers, eventually changing permeability values (Taghiyari 2014). A statistically significant difference (at 95% level of confidence) was observed between the specific gas permeability in MDF panels made from kenaf bast and those made from core. Specific gas permeability in the panels made from kenaf bast was significantly higher (at 95% level of confidence) than in the panels made from kenaf core (Figs. 2a and 2b). The highest and lowest gas permeability values in panels made from kenaf bast were observed in the RP7-RT3 and RP7-RT5 treatments, respectively (Fig. 2a). In the panels made from kenaf core, the highest and lowest gas permeability values were found in the RP3-RT5 and RP7-RT3 treatments, respectively (Fig. 2b).



a



b

Fig. 2. Specific gas permeability values in the panels made from (a) kenaf bast and (b) kenaf core. Data provided for the mean ± standard deviation (RP=refining pressure; RT=refining time)

The significantly lower permeability in panels made from kenaf core was primarily related to fiber properties. Fibers obtained from kenaf core had a significantly higher flexibility ratio (Nayeri *et al.* 2013), resulting in a tendency of fibers to conform to the surfaces of adjacent fibers. This was the root reason why the core fibers could collapse more easily and therefore better integrate into the panels and MDF-matrix (Figs. 3a and 3b). The collapse and consequent higher integration into the MDF-matrix resulted in fibers with more surface connection area among them. Eventually, the empty voids and spaces through which fluids (air or water) could pass decreased substantially. Therefore, fluids could not transfer through the matrix as easily as they could pass through panels made from kenaf bast, with its lower-flexibility fibers. The higher flexibility ratio, as well as the higher surface connection area, also resulted in higher mechanical properties (Nayeri *et al.* 2013). Ash content was also reported to be lower in kenaf core compared with kenaf bast (Abdul Khalil *et al.* 2010). Lower ash and extractive contents allowed the resin to make better bonds among fibers in the MDF-matrix, resulting in higher surface-to-surface contacts; eventually, fluid could not pass through the matrix easily and permeability drastically decreased in panels made from kenaf core. It was previously reported that breaking down of the resin resulted in significant change in gas permeability and the correlation between air and liquid values (Taghiyari 2014).

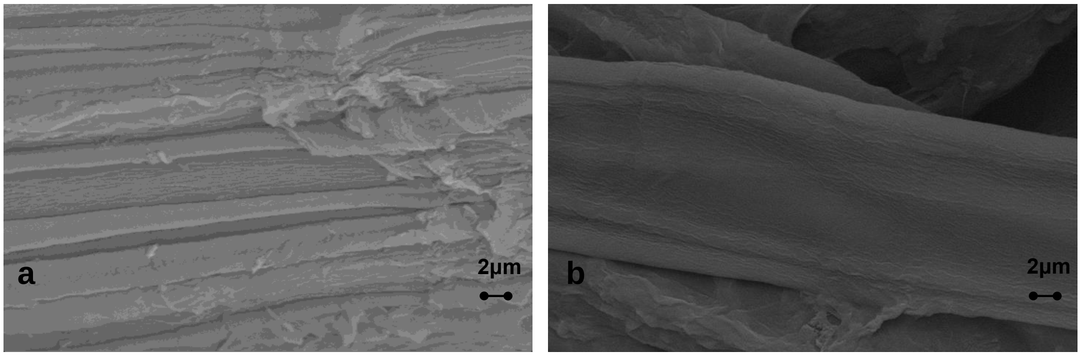


Fig. 3. SEM micrographs showing (a) a collapsed cell-wall in kenaf core fiber and (b) the straight, intact fibers of kenaf bast (Mag. × 2000)

Cluster analysis based on all physical and mechanical properties, as well as permeability values, revealed a distinct and significant difference between panels produced by kenaf bast and those produced by core (Fig. 4a). This proves that the overall properties of panels made from the bast or core sections of the kenaf stem was significantly different ($p < 0.05$), making their potential applications different for particular purposes. Cluster analysis based on only mechanical properties showed the same distinct and significant difference between panels made from bast and those made from core (Fig. 4b); however, cluster analysis based on only physical properties demonstrated that panels made from kenaf core with a refining pressure of 3 bars clustered more similarly to panels made from kenaf bast rather than those made from kenaf core under different refining pressures (Fig. 4c). It can therefore be concluded that permeability has the potential to show the overall properties of panels made from different parts of the kenaf stem and their categorization. Moreover, the quality of the fibers and the way they are connected in the MDF-matrix would impact mechanical properties and permeability more similarly than they would affect physical properties.

The highest and lowest water absorption were reported to be in MDF panels made from kenaf bast RP7-RT3 (28.8%) and kenaf core RP7-RT5 (14.6%), respectively (Nayeri *et al*. 2013, 2014). All panels made from kenaf bast showed substantially higher water absorption in comparison to the panels made from kenaf core. In fact, regression analysis of specific gas permeability values *versus* water absorption in the twelve MDF treatments (panels) indicated highly significant R^2 values (Fig. 5a). As to the thickness swelling, the highest and lowest TS values were found in panels made from kenaf core RP3-RT3 (91.5%) and kenaf core RP7-RT5 (63.2%), respectively. TS values of panels made from kenaf bast were in between these two maximum and minimum figures.

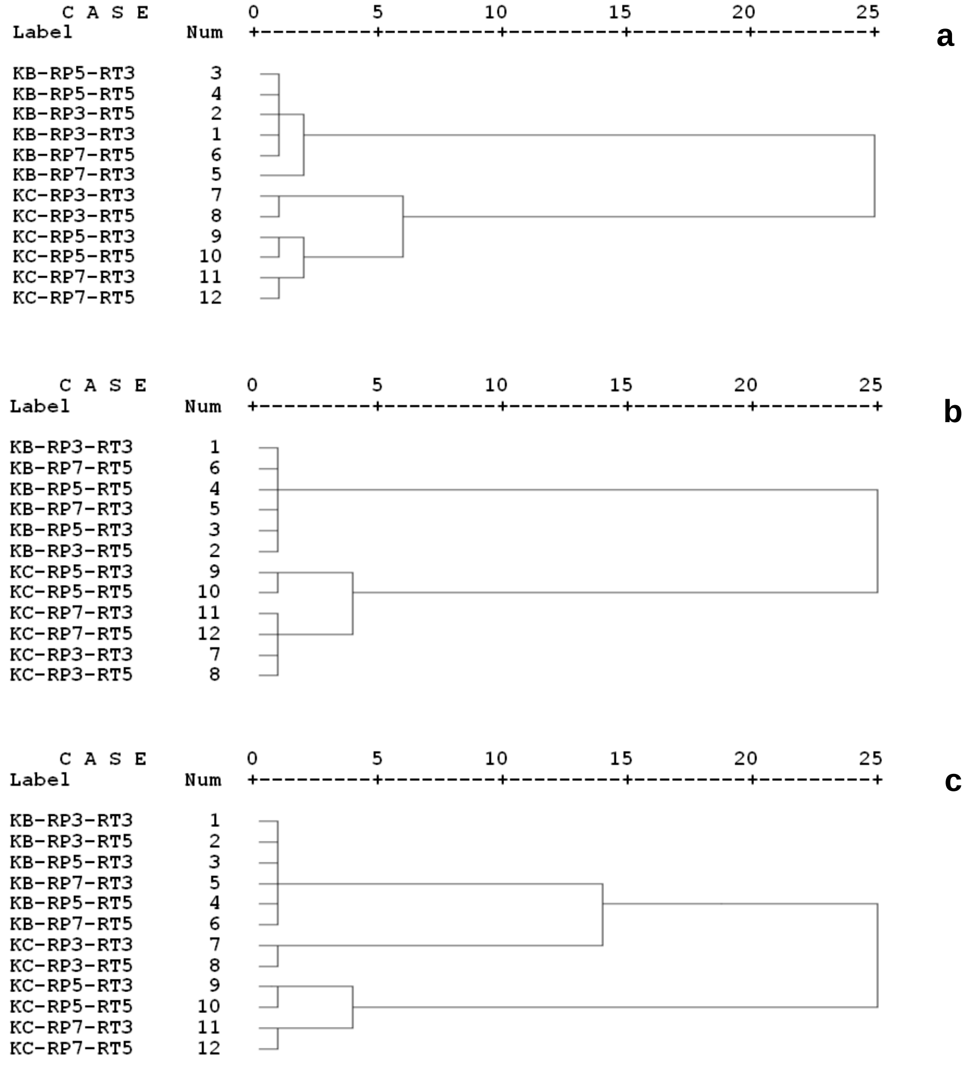


Fig. 4. Cluster analysis among the twelve treatments of MDF based on (a) all physical and mechanical properties as well as permeability values; (b) mechanical properties; and (c) physical properties of WA and TS (KB=kenaf bast; KC=kenaf core; RP=refining pressure; and RT=refining time)

Correlation between gas permeability and thickness swelling was very low and not statistically significant (Fig. 5b). This indicates that gas permeability was closely related to the behavior of water molecule penetration into the MDF-matrix and the empty voids among kenaf fibers in MDF texture. The thickness swelling, however, was related to the actual absorption of water molecules by the cell-wall components, having little to do with the transfer of fluids through the MDF-matrix. Therefore, an insignificant correlation was found between permeability and TS. Moreover, an insignificant correlation was found between WA and TS (Fig. 5c), confirming that the two physical properties reacted significantly differently to water molecules. Furthermore, high correlations were found between most of the specific gas permeability and the mechanical properties (Fig. 5d); this also confirmed the distinct significant difference between the panels made from kenaf bast and kenaf core (Figs. 4a and 4b).

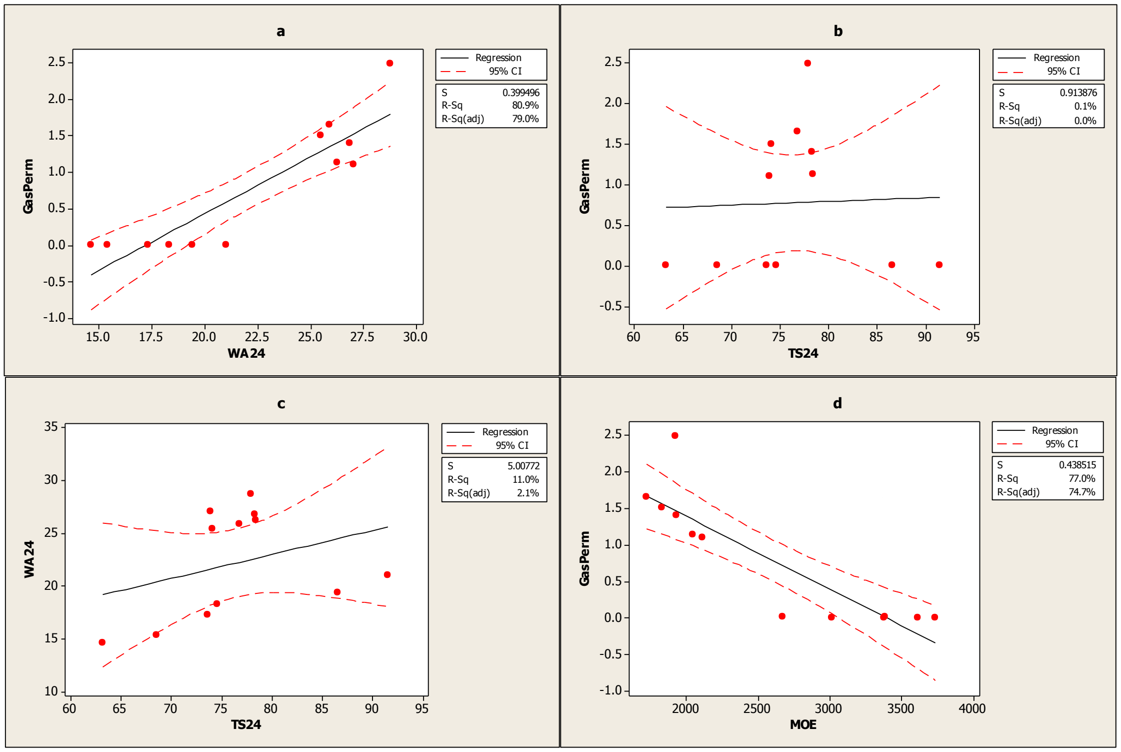


Fig. 5. Fitted-line plots describing the relationship between specific gas permeability and physical and mechanical properties in the twelve MDF treatments (GasPerm, specific gas permeability; TS24, thickness swelling after 24 h of immersion; WA24, water absorption after 24 h of immersion; MOE, modulus of elasticity)

CONCLUSIONS

1. Specific gas permeability was significantly lower ($p < 0.05$) in MDF panels made from kenaf core compared with those made from kenaf bast.
2. The higher flexibility ratio of the kenaf core made for easier collapse of the fibers, and eventually better surface connection was provided among kenaf fibers in the MDF-matrix produced, resulting in a significant decrease ($p < 0.05$) in permeability.
3. A highly significant correlation was found between specific gas permeability and water absorption, showing that the penetration of water molecules was closely related

to the transfer of fluid through the MDF-matrix. Moreover, highly significant correlations were also observed between gas permeability and mechanical properties, demonstrating that the collapse and better integration of fibers into the matrix eventually caused better connection between and integrity in the fibers, resulting in improved mechanical properties and a significant decrease in permeability and water absorption.

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