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Effects of Density Variation on the Physical and Mechanical Properties of Empty Fruit Bunch Cement Board (EFBCB)

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ABSTRACT

A cement board is a composite material mostly comprised natural fibre and cement. Cement board is mainly used in roofing, raised floors, dropped ceilings, prefabricated structures, office containers, and other building components. Fibres in cement composites from discarded palm oil fruit bunches have been used to increase the quality of construction materials. Therefore, the impact density of the natural fibre cement board is essential to enhance the physical and mechanical properties. However, research on untreated fibre at various densities has not been compressively discussed in previous studies. Therefore, this research used empty fruit bunch (EFB) fibre in manufacturing empty fruit bunch cement boards (EFBCB) with a cement-to-fibre ratio of 3:1 and thickness of 12 mm. Three target density variations, 1100 kg/m^3, 1200 kg/m^3 and 1300 kg/m^3, were applied in this study to obtain their effect on physical and mechanical properties. The results revealed EFBCB sample with a target density of 1300 kg/m^3 showed the most promising results. This sample's average thickness is 12.38 mm after a 28-day curing period. Besides, at 1300 kg/m^3 target density, EFBCB achieved the lowest thickness swelling (TS) value at 1.82%, highest internal bonding (IB) at 0.164 N/mm^2, highest modulus of elasticity (MOE) and modulus of rupture (MOR) at 1398 N/mm^2 and 3.51 N/mm^2, respectively. Thus, increasing the cement board density and improving the physical and mechanical properties of EFBCB. This study demonstrates that EFB has the capacity to be one of the potential natural fibres for green building materials.

Keywords: Empty fruit bunch (EFB), empty fruit bunch cement boards (EFBCB), mechanical properties, physical properties, variation density

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INTRODUCTION

Oil palm, by its scientific name, *Elaeis guineensis*, has become one of the most important commodities in Malaysia (Olusegun et al., 2012). Concurrently, the palm oil industry that forms the economic backbone of Malaysia also contributes to a large amount of solid waste in landfills. According to the Malaysian Palm Oil Industry (MPOB), oil palm production in Malaysia has increased over the years, from 4.1 million tonnes in 1985 to 6.1 million tonnes in 1990 to 27.8 million tonnes in 2019. However, 2020 was a challenging year for the MPOB due to the global outbreak of the COVID-19 pandemic. The industry experienced a temporary slowdown in the first half of 2020 in export demand and prices. Still, towards the second half, the scenario changed due to the re-opening of the global economic sectors with the relaxation of movement restrictions (MCO) coupled with the government's initiative under the National Economic Recovery Plan (PENJANA). Data from the Department of Statistics, MPOB (2020), the total export of palm oil in 2020 amounted to 26.7 million tonnes, lower by 4.1% than the 27.9 million tonnes exported in 2019. It is due to lower demand caused by the COVID-19 pandemic. It shows that oil palm production is still in demand yearly, even during the COVID-19 pandemic.

Along with technological development, natural fibres such as palm oil fibre have become the most valuable crop. This natural fibre composite is a cost-effective, sustainable material with low energy consumption and is environmentally friendly (Samsudin et al., 2016; Peter et al., 2020). Thus, further developments for a long-term strategy are needed for natural fibre potential as a material in structural and non-structural applications (Akasah et al., 2019). Natural fibres are typically incorporated into the cement matrix in discrete or discontinuous forms. The primary function of these fibres is to reinforce, that is, to increase tensile strength and prevent the matrix from cracking (Amel et al., 2017). Thus, transforming these wastes into cement-bonded particle boards has been found to be effective in wood waste management and producing eco-friendly development materials (Egbewole, 2017; Ogunjobi et al., 2019). Typically, due to its flexibility, such as resistance to decay and fire, good dimension stability, good insulation properties, availability, lightweight, low cost, zero-carbon footprint, toughness, biodegradability, non-toxicity to the ecosystem, thermal insulation, improved acoustic insulation and high recyclability (Momoh & Osofero, 2020; Ajayi & Badejo, 2005; Papadopoulos et al., 2006).

Cement-bonded composites have come in various forms, including cement-bonded fibreboards and particleboards. The product is easily obtained because it comes from multiple sources and is thoroughly optimised access. According to Lin (2009), empty fruit bunch (EFB) waste is mainly used as plantation fertiliser. EFB fibre may also be used as insulation, a wall divider, medium-density fibreboard, or in housing applications.

Based on Coutts's (2005) review, a study by James Hardy stated that fibre cement boards were formerly manufactured from asbestos. According to Ogonjabi et al. (2019), asbestos fibres were previously commonly used in construction because of their low cost, relatively strong chemical, physical, and mechanical durability, and long and readily manipulated fibre. Asbestos has been utilised in sheeting/cladding, roofing, thermal and electrical insulation, moulded fittings, water cisterns, rainwater gutters, coatings, and other goods (Coutts, 2005). However, due to health and environmental concerns, efforts have been directed toward sourcing environmentally friendly and socially acceptable alternative materials. To address the issues, wood and other non-wood materials in the form of fibres or particles have been widely used with cement matrices to produce various construction materials (Asasutjarit et al., 2009; Garcez et al., 2016). The major benefit of cement boards is that they do not swell or curl when wet due to their superior drying characteristics (Akinyemi & Osasona, 2017). It is also commonly utilised in construction since it has a longer lifespan than paper-lined gypsum products and will not mould or physically degrade due to moisture or leaks. Cement boards also have the drawback of weighing in square meters and being more expensive than paper-based gypsum due to their long-term impacts (Azni et al., 2015).

Previous research concentrated more on using EFB as building materials in the form of medium-density boards and insulator boards (Khalil et al., 2010; Ibrahim, 2014) and EFB in concrete (Mayowa & Chinwuba, 2013). Furthermore, Onuorah et al. (2015) have previously researched EFB cement board, to which they have found that the mean value for MOR (3.08-16.82 MPa), MOE (2515–5291 MPa), IB (0.28–0.75 MPa) and TS (1.36–4.23%). While Peter et al. (2020) also resulted in the finding ranges in modulus of rupture (MOR) of 3.98–9.11 MPa, modulus of elasticity (MOE) of 1056–4699 MPa, internal bonding (IB) of 0.28–0.53 MPa and thickness swelling (TS) of 1.66–9.25%. Therefore, from the standpoint of mechanical and physical properties, EFB fibre also has good potential as a reinforcement of wood-based material replacement for cement board production. Based on prior research, natural fibres such as EFB fibre have been identified as an alternative material that can replace asbestos. The characteristics of EFB, which have poor thermal conductivity and superior thermal insulation, have also been devised to manufacture high-strength materials, making them appropriate for use as reinforcing materials for cement boards (Azni et al., 2015).

The more immense fibre content in cement mixtures will impact the characteristics of the cement products. This paper attempts to investigate and determine the optimal density of fibre that might contribute to the best possible performance of the finished product. Presumably, aside from studied attempts to construct empty fruit bunch cement boards (EFBCB), there are extremely few and challenging to locate published research concerning the influence of varied fibre density on the EFBCB characteristics. Hence, this study aimed to see if using a high proportion of oil palm EFB fibres might improve the cement board characteristics.

MATERIALS AND METHODS

Material Preparations

The raw material for this study was oil palm EFB obtained from Pamol Kluang Palm Oil Mill, Kluang, Malaysia. All preparation and production works of EFBCB were carried out at the Timber Fabrication Laboratory and Construction Engineering Laboratory, Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia. Figure 1 shows the condition of the fibre from the source point and after being processed. It was sun-dried after transporting the raw EFB from the mill for 2 to 3 days, depending on the weather conditions to reduce the excessive moisture. The dried EFB was cut to shorter fibre using the shredder and turned into finer fibre size using the hammer mill machine. Finally, the sieving process was conducted duct using sieve equipment to remove dusk fibres. Raw EFB needed to undergo these processes due to its original conditions, which might cause difficulties in establishing good bonding between the fibre and the cement during fabrication.

Figure 1. Preparation of fibre from raw to processed fibre

Sample Preparation

The fabrication of EFBCB composites uses a mixture of portland cement, water, and EFB fibre. In this study, the density of the samples varied between 1100–1300 kg/m^3 (Asasutjarit et al., 2007). The samples were made in different densities to test the cement board's performance. Nine samples with dimensions of 350 mm x 350 mm x 12 mm with the target density of 1100 kg/m^3, 1200 kg/m^3, and 1300 kg/m^3 were manufactured using the same cement-to-fibre ratio (3:1). EFB fibre water and cement are the materials that require for the sample fabrication need to weight before the mix. The total weight of the materials is determined by the ratio 3:1, which represents cement to fibre content. This ratio is used due to promising results of bending strength (MOR) obtained by Owoyemi et al. (2020) and Ogunjobi et al. (2019). Based on research by Akasah et al. (2019) and Onuorah et al. (2015), targeted density is achieved by maintaining the same total weight of the materials used in the mixture. The targeted density can be achieved using a calculation based on the weight of the sample divided by the volume. According to BS EN 323 (1993), the minimum density of a cement board should be equal to or greater than 1000 kg/m^3. The three densities of samples are differentiated by the total weight of the mixture according to the targeted densities of 1100 kg/m^3, 1200 kg/m^3 and 1300 kg/m^3 using the same cement-to-fibre ratio of 3:1. Based on three samples fabricated for each targeted density, the average density of 1060 kg/m^3, 1239 kg/m^3 and 1313 kg/m^3 were obtained. Table 1 shows the calculation of the design mix for EFBCB used in this research according to the targeted density. Distilled water is used to optimise the hydration rate of cement with 40% water based on cement weight (Akasah et al., 2019).

Table 1
Design mix for EFBCB

Density (kg/m^3)	1100	1200	1300
Sample size	350 x 350 x 12 mm	350 x 350 x 12 mm	350 x 350 x 12 mm
Volume sample	1.47 x 10^{-3} m^3	1.47 x 10^{-3} m^3	1.47 x 10^{-3} m^3
Dry weight	≈1617 g	≈1764 g	≈1911 g
Cement: EFB	$3x + x$ = Dry weight	$3x + x$ = Dry weight	$3x + x$ = Dry weight
3:1	1212.75 g : 404.25 g	1323 g : 441 g	1433.25 g : 477.75 g
Water	= 606.38 g	= 661.5 g	= 716.63 g

The fabrication method for Empty Fruit Bunch Cement Board (EFBCB) used in this study applied to the fabrication method used by Ashori et al. (2012), Onuorah et al. (2015), and Ghofrani et al. (2015). Recently, the same fabrication method was also used by Akasah et al., (2019) to investigate the effect of EFBCB density using different EFB fibre sizes.

This study only focused on various densities without segregating the fibre sizes. All materials (EFB fibre, water and cement) are weighted accordingly and mixed using the mechanical mixer. The raw ingredients were blended for 3 minutes in a mixer before adding the water. Then, the cement was added and mixed for about 10 minutes, which Ghorfani et al. (2015) recommended. It was then pre-formed into a wooden mould using a wire mesh and a manual lay-up procedure (Peter et al., 2020). Before being transported to a 50 tonne/m^2 cold compressor machine, the mixture was pre-pressed with another polythene sheet on top of it, with the metal plate mould put on the upper half. The cement board mixture was compressed at a 180 mm/min pressure rate for around 5 to 7 minutes until it reached the desired thickness (Peter et al., 2020). Before the mixed materials were compacted, a 12 mm thick spacer was inserted between the steel mould. This process reduces the sample's height and helps stabilise the pressing surface. The specimen of the cement board was de-clamped after 24 hours, stacked horizontally, and cured at ambient temperature with relative humidity for 28 days allowing it to cure and increase its strength (Ghofrani et al., 2015; Onuorah et al., 2015). The EFBCB fabrication process is described in Figure 2.

Figure 2. EFBCB fabrication process. (a) Weighting material, (b) Mixing process, (c) Spreading process, (d) Flattening process, (e) Pre-compact process, (f) Pre-forming process, (g) Compressed using compression machine, (h) Clamped process, (i) Curing process

Thickness Monitoring (TM)

Thickness monitoring (TM) is used to investigate the density impact on the dimensional stability of EFBCB. This monitoring procedure was carried out every two days after the EFBCB had been subjected to a curing process for 28 days (BS EN 324-1:1993), and readings were collected using a digital vernier calliper throughout the process until a consistent reading was obtained. This technique was performed on three samples. The average reading of the three samples was used to calculate the thickness. The thickness of the sample was recorded on every four sides of the sample. Equation 1 was used to calculate the thickness of the cement board:

$$\text{Thickness Monitoring (TM)} = \frac{S\,1 + S\,2 + S\,3}{3} \tag{1}$$

where S is the average thickness of each sample.

Density Test

A density test was conducted after the curing process. This test aimed to analyse the dimensional stability of the EFBCB besides the physical properties themselves. The density testing procedure is based on the BS EN 32 (1993) standard. This sample's dimensions are square at 50 x 50 mm. Then, the weight and thickness of the sample were recorded. The formula for this test is in Equation 2:

$$\text{Density, } \rho = \frac{\mathrm{m}}{V} \tag{2}$$

where m is the sample mass, and v is the sample volume.

Thickness Swelling (TS)

Due to the physical properties of EFBCB, a thickness swelling (TS) test was performed. By referring to the BS EN 317 (1993) standard, the TS test was to determine the water absorption of the samples after going through the curing process for 28 days. The sample was soaked in the water for 24 hours. The thickness of the samples before and after being immersed in water for 24 hours was recorded. The formula in Equation 3 is used to calculate the TS values:

$$\text{TS} = \frac{t2 - t1}{t1} \text{ x } 100\% \tag{3}$$

where $t1$ is the thickness before being immersed, and $t2$ is the thickness after being immersed.

Internal Bonding (IB)

This test was carried out to determine the strength of the bond between cement and EFB fibre. The test piece's dimension is a square, with each side length of 50 mm. Each test piece (top and bottom surface) was bonded to the steel-loading block using a suitable epoxy. The pulled load was then applied to the sample at a consistent action rate using a Universal Testing Machine guided by BS EN 319 (1993). The experiment was done until the sample failed. This test aimed to get the ultimate load on the sample before it breaks. Equation 4 is used to calculate the IB values:

$$\mathrm{IB} = \frac{P}{wl} \tag{4}$$

where *P* is the maximum load, *w* is the width, and *l* is the length.

Modulus of Elasticity (MOE) and Modulus of Rupture (MOR)

After the curing process, the sample was cut to the prescribed size, and its mechanical characteristics of MOE and MOR were evaluated by BS EN 310 (1993). A static bending test was performed to establish the maximum load applied to the midpoint of the specimen that was simply supported. According to BS EN 310 (1993), the dimension of the specimen to be measured is 300 mm x 50 mm x 12 mm. Equations 5 and 6 are formulas to calculate the MOE and MOR values:

$$\mathrm{MOE} = \frac{L^2 \Delta \mathrm{W}}{4bt^3 \Delta S} \tag{5}$$

where L is the distance between the centre of support, ΔW is the increment load, ΔS is the increment of deflection at the midpoint corresponding to ΔW, b is the width of the test piece, and t is the thickness of the test piece.

$$\mathrm{MOR} = \frac{3WL}{2bt^2} \tag{6}$$

where W is the maximum load, L is the distance between the centre of support, b is the width of the test piece, and t is the thickness of the test piece.

RESULTS AND DISCUSSION

Effects on Physical Properties of EFBCB

The dimensional stability of EFBCB was interpreted and discussed in terms of physical properties such as Thickness Monitoring (TM), Density, and Thickness Swelling (TS) performance for each density. The TM procedure was carried out every two days after the EFBCB was subjected to a curing process for 28 days. The readings were collected using a digital vernier calliper until a consistent reading was obtained. Meanwhile, the density test was conducted after the curing process. The TS data was calculated by measuring the increase in thickness of the test piece after completing the water immersion process. The British Standard BS EN 324-1 specified all tests:1993, BS EN 323 (1993) and BS EN 317 (1993), respectively.

Thickness Monitoring (TM)

The design thickness for this study is 12 mm with an allowed thickness of ± 1 mm (BS EN 324-1, 1993), which means that the thickness must be between 11 mm and 13 mm to be suitable for use as building components in construction. Figure 3 shows the thickness monitoring results of samples in this study. Each sample recorded inconsistent readings towards the 28 days of curing. The surrounding temperature (ambient temperature) may influence the inconsistent readings of the sample thickness (Akasah et al., 2019). However, the sample with a target density of 1300 kg/m^3 showed the most horizontal graph reading, leading to a much more consistent reading to achieve the optimum thickness of EFBCB, which is 12 mm. Based on the results, the high density is one of the factors that leads the panel fabrication to achieve an optimum thickness reading due to the highest amount of cement mixed into the sample (Akasah et al., 2019). Cement is the primary binding agent for the EFB fibres in EFBCB samples (Wahab et al., 2015). Based on the results, it can be concluded that the stability of EFBCB increases when the density of EFBCB increases.

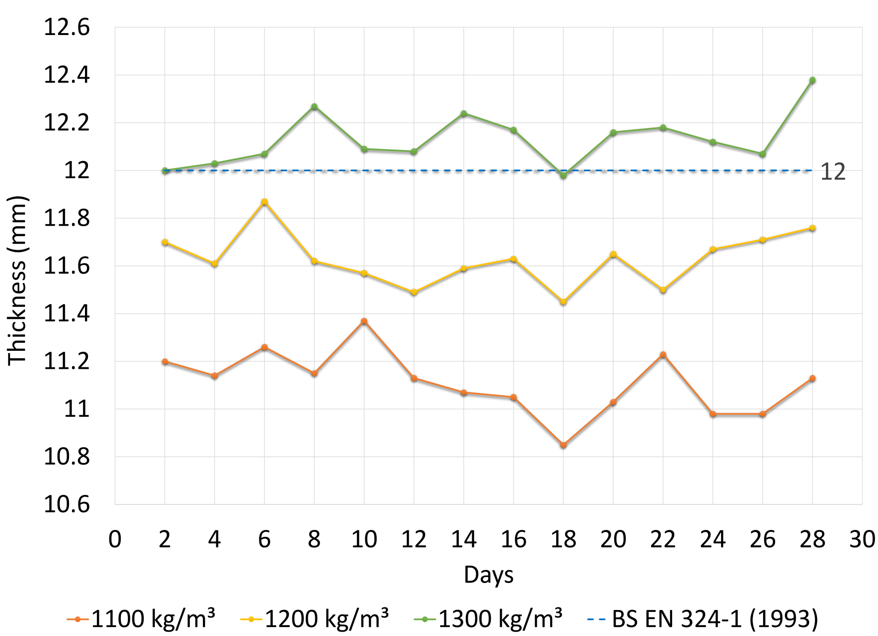

Figure 3. Thickness monitoring of EFBCB for 28 days

Density Test

The density of each sample is measured after 28 days of the curing process. The curing process allows maintenance of the sample's stability (Soydan et al., 2018). Density is measured by carefully cutting the samples into 50 mm x 50 mm. Then, samples are weighed and measured in length, width, and thickness using a vernier calliper. This density test is according to BS EN 323 (1993) standard, where the minimum requirement for a cement board density is 1000 kg/m^3. The results of the density test are shown in Figure 4.

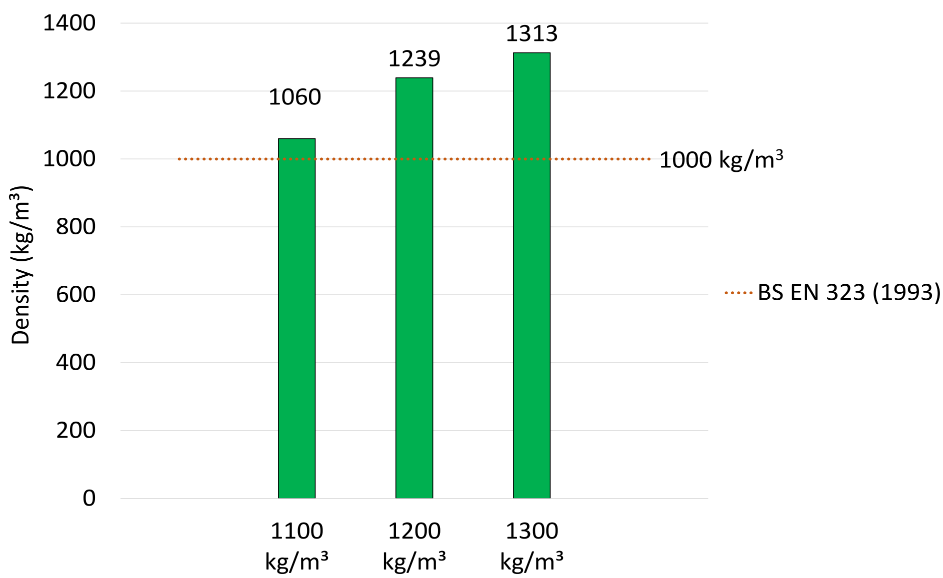

Figure 4. Average density of EFBCB

Thickness Swelling (TS)

Figure 5 shows the sample with a target density of 1100 kg/m^3 obtained 4.49% of thickness swells, which is larger than the other two samples. Voids are commonly found in low-density particleboards that generate areas to allow more water absorption (Loh et al., 2010). The low-density board's composition enhances water penetration, resulting in high water absorption, which causes the board to swell and, consequently, raises the thickness swelling (Wong et al., 2009). Hence, this research evidence that the highest density sample with a target density of 1300 kg/m^3 and 1.82% of thickness swell is the most recommended density for EFBCB with fewer TS effects that are almost complied with the recommended TS value as outlined in the BS standard requirement.

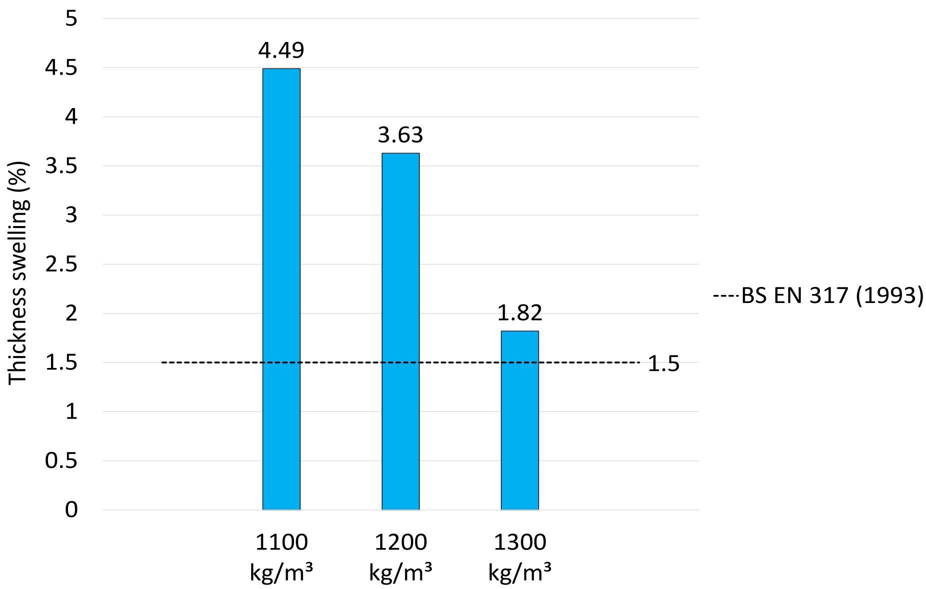

Figure 5. Thickness swelling effects of EFBCB at different target densities

Effects on Mechanical Properties of EFBCB

The mechanical characteristics of EFBCB based on densities are interpreted and discussed in terms of Internal Bonding (IB), Modulus of Rupture (MOR) and Modulus of Elasticity (MOE). The result for each targeted density is averaged from nine (9) EFBCB samples with a surface area of 50 mm x 50 mm for the IB test and using 300 mm x 50 mm for MOR and MOE testing. Testing is conducted following the British Standards BS EN 319 (1993) for IB and BS EN 310 (1993) for MOR and MOE.

Internal Bonding (IB)

Internal bonding test on the cement board samples aims to determine the internal bonding strength of the cement boards perpendicular to its surface when pressure is applied until cracks appear. The value was measured by dividing the maximum load at breaking by the sample's cross-sectional area. This testing was conducted based on the BS EN 319 (1993) procedure. Figure 6 shows that as the density of the board increase, the IB values also increase, with the EFBCB sample having a target density of 1300 kg/m^3 obtaining the highest IB at 0.164 N/mm^2 compared to the other two samples. According to Wahab et al. (2015), the bonding ability is associated with the EFBCB density. Thus, lower IB values obtained by the low-density cement boards were due to higher voids formed in the material. Those voids have caused the inter-fibre bonding to be ineffective (Ashori & Nourbaksh, 2008). Besides, inadequate compaction may also cause many of the inter-particle voids to be left empty. Better compression and tighter particle interactions are much greater for fine and mixed particles, which may enhance the cement board's performance (Gupta et al., 2011).

This research obtained low IB results for all EFBCB samples at all three different target densities. The values are slightly below the standard requirement for a cement board, as recommended by BS EN 319 (1993), at 0.5 N/mm². The low IB shows incompatibility between the cement and the fibre in the mixture using 3:1 ratio.

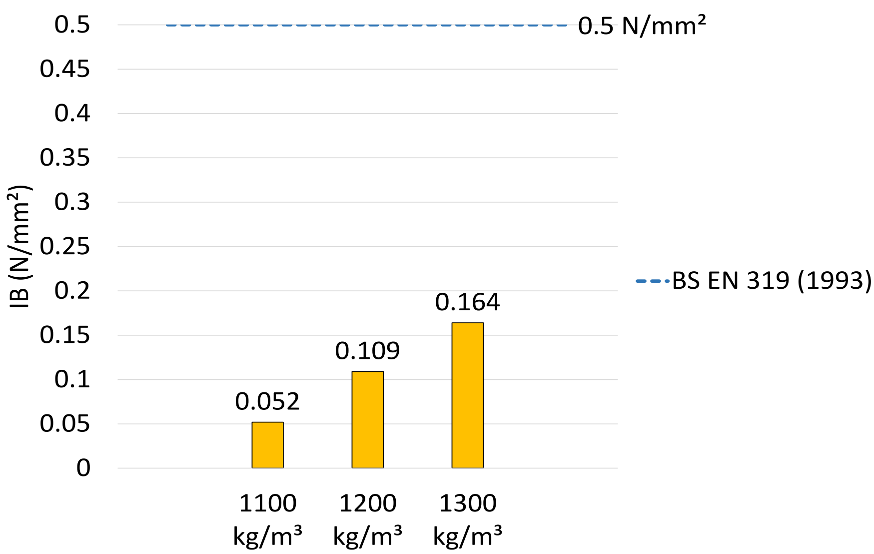

Figure 6. Internal bonding of EFBCB based on the different target density

Modulus of Elasticity (MOE) and Modulus of Rupture (MOR)

The amount of elasticity after the load applied is released and its resistance to bending define the modulus of elasticity (MOE) of an EFBCB. Meanwhile, the modulus of rupture (MOR) measures the highest load-carrying capability observed when stress is applied to a crack sample. This testing aims to determine the total strength of cement boards compared to the MOE, which only tested deflection but not the final strength of EFB cement boards. Testing was conducted according to BS EN 310:1993 guidelines.

Table 2 shows the result of the MOE and MOR for the three different densities. The sample with a target density of 1300 kg/m³ had a greater average MOE value of 1398 N/mm². MOE is directly proportional to the density of the cement board, as described in a study by Wahab et al. (2015). When the MOE value is high, the board appears to be brittle; when the value is low, they tend to be ductile or flexible (Yang et al., 2003; Rasat et al., 2011). The results obtained described MOE values for all samples compared to the requirement stated in the BS EN 310:1993, Class 1: 4500 N/mm² and Class 2: 4000 N/mm².

Similarly, average MOR values for the sample with higher density shows better result compared to the lower density samples with an average MOR=3.51 N/mm^2. Based on the results, it can be concluded that the MOR value increase as the density of the sample increases. Findings from this research show that the MOR and MOE values are directly proportional to the density. Increase in the board density resulting in increasing the MOR and MOE value. The same finding was also obtained by Wahab et al. (2015); as the density of the boards increased, the MOE and MOR also increased. However, the MOR values for all samples are below the recommended value as stated in the standard, which is at 9 N/mm^2.

Table 2
Value of MOE and MOR for three different density

Target Density (kg/m^3)	Actual Density (kg/m^3)	Average Density (kg/m^3)	Mixing Ratio	MOE, N/mm^2		MOR, N/mm^2	
				Actual MOE	Average MOE	Actual MOR	Average MOR
1100	1007	1060	3:1	405.1	1006	2.39	3.1
	1051		3:1	1307		2.66	
	1121		3:1	1306		4.25	
1200	1020	1239	3:1	1122	1105.13	3.21	3.42
	1311		3:1	733.4		2.46	
	1385		3:1	1460		4.59	
1300	1214	1313	3:1	2212	1398	5.35	3.51
	1397		3:1	835		2.66	
	1327		3:1	1147		2.53	

CONCLUSION

Density had significant effects on the physical and mechanical properties of EFBCB. In this study, EFB cement boards with a target density of 1300 kg/m^3 show better performance than the other samples in terms of thickness stability, thickness swelling internal bonding, modulus of rupture and elasticity. In order to produce a higher-density panel, more cement and fibre are needed to achieve the target density. Since the same thickness is applied to all samples with regards to their target density, higher pressure needs to be applied during the fabrication process for the sample with a target density of 1300 kg/m^3, thus resulting in fewer voids left in the sample. Furthermore, voids in the EFB cement board generate areas that allow water to be absorbed, thus swelling the thickness. Since the EFB cement board with a target density of 1300 kg/m^3 contained less voids, this sample's mechanical properties are much better than the others. Density shows a directly proportional relationship with the internal bonding, modulus of rupture and modulus of elasticity of EFB cement board at the same thickness and cement: fibre ratio. Even though the results are not very promising, this study has successfully shown that EFB fibre has a significant potential to be utilised as a green building material in the making of the building panel. However, further investigation is still needed to improve the mechanical properties of EFB cement boards to ensure their sustainability in the construction market.

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