Sustainable Development of Cement-Bonded Boards: Evaluating Physico-Mechanical Properties of Waste Paper and Bagasse Composites

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The overexploitation of forest resources for construction purposes has led to the utilization of waste materials for recycled composites. This study examined the sustainable development of Cement Bonded Board from bagasse and waste paper. Three levels of mixing ratios (MR) 2:1, 3:1, and 4:1, were used for this study. Particles from these wastes were milled, pre-treated, and dried, after which they were weighed and put in polythene. Particles were mixed with a mixing machine and the mould was spread on plates which have been previously covered with polythene sheets. The plate is then transferred to the wooden press to press at a pressure of 1.23N/mm^2. After pressing for 24 hours, the mould plate is removed from the press and mould and allowed to set for 28 days. Boards produced were cut into test samples. Test were done according to ASTM D 1037-06a and ASTM D 7519-11. The results showed that MOE and MOR increased with an increase in MR. For paper, the MOE recorded showed that 4:1 has the highest value of 4154.97 N/mm^2 and 2:1 with the lowest value of 2173.93 N/mm^2 while for MOR 4:1 also has a value of 4.74 N/mm^2 and 2:1 has the lowest value of 9.07 N/mm^2. For bagasse, the MOE recorded showed 4:1/486.06 N/mm^2 and 2:1/271.53 N/mm^2 while for MOR 4:1/ 2.05 N/mm^2 and 2:1/ 0.82 N/mm^2. However, TS and WA had an inverse relationship MR for bagasse (2:1/ 6.11 %, 4:1/4.8 %) while for paper TS (2:1/2.24 %, 4:1/1.75 %). WA for bagasse (4:1 /28.30 %, 2:1/ 35.56 %) while for paper (4:1 /25.60 %, 2:1/ 39.02 %). The strongest and most dimensionally stable boards were produced at the highest mixing ratio of bagasse and paper. These two waste materials can be utilized in the production of sustainable materials that can be used in eco-friendly construction.

Keywords: Sustainable materials, sustainable composites, eco-friendly construction, dimensionally stable, modulus of rupture, modulus of elasticity

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Introduction

Recently, considerable changes in the housing and building construction industries have been taking place. Particularly, wood-based materials and composite panel products bonded with either organic or inorganic binders are gaining importance (Tobish *et al*., 2023). The most widely used inorganic-bonded composites are those bonded with Portland cement. Portland cement, when combined with water, immediately reacts in a process called hydration to eventually solidify into a solid stone-like mass. Successfully marketed Portland-cement bonded composites consist of both low-density products made with excelsior and high-density products made with particles or fibres. The low-density products may be used as interior ceiling and wall panels in commercial buildings (Stark & Cai, 2021). Low-density composites bonded with Portland cement offer sound control and can be quite decorative. In some parts of the world, these panels function as complete wall and roof decking systems. The exterior and interior of the panels are plastered. High density panels can be used as flooring, roof sheathing, fire doors, load-bearing walls, and cement forms. Fairly complex shapes can be moulded or extruded, such as decorative roofing tiles or non-pressure pipes (Cai, 2011). The shortage of resources in general is a fact that forces the utilization of recycled wood (Wang *et al*., 2020). Because of the increasing scarcity of wood raw materials, the effort to find wood substitutes is always encouraged.

Construction is a material-intensive endeavour that requires substantial quantities of resources. Consequently, the use of lignocellulosic waste, such as Kraft paper, in the production of cement-bonded construction materials is a viable alternative to disposal (Chen *et al.*, 2022). Synthetic fibres and diverse agricultural waste fibres such as banana stalk fibre, bagasse, grass, and banana sucker, can also serve as materials for cement-bonded boards (CBBs). The output rate of agricultural waste in our society is escalating. A substantial quantity of agricultural and other waste is being disposed of in the environment, resulting in environmental nuisances and posing threats to society. The indiscriminate dumping of waste items is increasingly concerning in our local environment (Ifeoluwa, 2019). The by-products (bagasse and waste paper) are consistently incinerated, resulting in air pollution. The combustion of such materials releases a significant quantity of carbon monoxide into the atmosphere, in addition to particulate matter and other air pollutants (Elehinafe *et al*., 2022). Diverting these resources to particle board production, rather than incinerating them, will promote environmental sustainability.

The utilization of agricultural and industrial waste for particle board production has been driven by its abundance in the country. Agricultural and industrial waste have been identified as renewable and eco-friendly biomass supplies that can alleviate the substantial demand for woody materials (Guo *et al*., 2024). Previously utilized agricultural leftovers encompass cereal straw, corn stalk, kenaf, rice husk, straw, and bagasse (Gupta *et al*., 2022). Nevertheless, minimal study has been conducted on the comparative analysis of industrial and agricultural residues in the manufacturing of cement-bonded boards. This study evaluated cement-bonded boards made from waste paper and bagasse, focusing on the physico-mechanical properties of the composites.

Literature Review

The use of waste in particleboard manufacturing signifies a notable progress in sustainable materials science, providing both waste valorisation and the creation of environmentally benign substitutes for conventional wood-based panels (Okeke *et al*., 2024). Given the waste management hierarchy, complete prevention and mitigation of waste generation is nearly unattainable; instead, reusing and recycling agro waste in construction can facilitate the prioritization of sustainable and resource-efficient practices, thereby diminishing the environmental impact of crop production and fostering a circular economy in waste management (Mainardis *et al*., 2022). The expanding worldwide population and rising demand for ecological and cost-effective building materials have compelled academics to investigate the viability of agro-industrial wastes as alternative raw materials. The examined literature highlights a diverse array of agricultural residues that have been extensively researched, including sugarcane bagasse (Fiorelli *et al*., 2019), rice husks (Hidayat *et al*., 2022), corn stover (Fatima Haq *et al*., 2022), peanut shells (Ercan *et al*., 2021), coconut fibres (de Souza *et al*., 2021), bamboo (Nasser *et al*., 2020; Guan *et al*., 2022), and wheat straw (Jové-Sandoval *et al*., 2023), among others. Sugarcane bagasse, a fibrous by-product of juice extraction, is primarily found in tropical and subtropical areas. The high cellulose content, between 32% and 44%, and hemicellulose content, ranging from 27% to 32%, render it an exceptional raw material for PB production (Loh *et al*., 2013). Sugarcane is the most cultivated crop, generating a surplus of bagasse, which has prompted significant research into its application in particleboard manufacturing. Fiorelli *et al*. (2019) proved the feasibility of creating high-quality multilayer PB using bagasse and coconut fibres, obtaining mechanical qualities that conformed to international requirements. Garzón *et al*. (2012) similarly examined the durability of bagasse-based particleboards, concluding that they demonstrated satisfactory dimensional stability and mechanical performance following accelerated aging testing. Rice husks, a by-product of rice milling prevalent in major rice-producing developing nations, possess distinctive characteristics owing to their high silica content of 15% to 20%, enhancing fire resistance and dimensional stability in particleboard (Mendes *et al*., 2010). Battegazzore *et al*. (2017) effectively engineered rice husk PBs exhibiting improved flame retardancy by a layer-by-layer functionalization method. This study emphasized the potential of rice husks as a sustainable raw material and a method to enhance the fire safety of particleboards. Additionally, Hidayat *et al*. (2022) investigated the application of natural rubber latex as a formaldehyde-free binder for rice husk-based panels, mitigating concerns regarding formaldehyde emissions from conventional adhesives. Maize stover, comprising stalks, leaves, and cobs remaining post-harvest, is abundantly accessible in numerous regions, as maize is the most extensively cultivated grain worldwide. The cellulose percentage ranges from 38% to 40%, and the lignin level varies from 7% to 21%, which confer favourable mechanical qualities for PB manufacture (Pode, 2022). Mayer-Laigle *et al*. (2021) examined the preservation of corn pith cellular architecture to enhance insulation qualities in agro-materials, illustrating the viability of maize stover as both a structural element and a thermal insulation medium in particleboards. Peanut shells, a by-product of peanut processing, possess a lignocellulosic composition appropriate for PB production. Ercan *et al*. (2021) investigated the formaldehyde emissions and combustion characteristics of peanut husk-based composite panels, illustrating their viability as eco-friendly building materials with minimal environmental impact. Coconut fibres, derived from coconut husks in tropical coastal areas of Asia, Africa, and South America, include high levels of lignin (41-45%) and cellulose (36-43%), providing superior mechanical qualities (Taha *et al*., 2016). Fiorelli *et al*. (2019) effectively integrated coconut fibres into multilayer particleboards, whereas Narciso *et al*. (2012) investigated their applicability in medium-density particleboard manufacture, concluding that coconut husks could partially substitute wood particles without markedly diminishing board characteristics. Bamboo, a quickly renewable resource extensively grown in Asia, Africa, and South America, possesses exceptional strength-to-weight ratios and inherent antibacterial qualities. Guan *et al*. (2022) created binder less bamboo particleboards using biological fermentation, tackling the issue of synthetic resin utilization and showcasing the feasibility of entirely bio-based particleboard production. Wheat straw, prevalent in numerous places worldwide, has been thoroughly researched for PB manufacture. Khorami and Sobhani (2013) examined the flexural performance of cement-bonded wheat straw boards, whereas Jové-Sandoval *et al*. (2023) investigated its application in earth-straw lightweight panels for enhancing the thermal properties of adobe walls, demonstrating the adaptability of wheat straw in diverse construction contexts. The incorporation of these varied agricultural wastes into PB production provides other benefits beyond waste valorisation. Numerous materials confer distinct attributes to the resultant particleboards, including augmented fire resistance from rice husks and enhanced acoustic properties from enzyme-treated fibres. The regional availability of various agricultural wastes facilitates the development of PB customized to locally sourced materials, potentially diminishing shipping expenses and related emissions. Nonetheless, there has been limited research on the comparability between industrial and agricultural waste. This study will investigate the sustainable development of cement-bonded boards from industrial and agricultural waste.

Materials and Methods

Bagasse waste was acquired from Ilorin Kwara State and transported down to Akure. The bagasse waste was dried and pre-treated at the composite laboratory of the Department of Forestry and Wood Technology, FUTA, Akure. Paper waste was also collected from the Akure environs. Portland cement, the binder, was bought from an authorized dealer in Akure. The chemical additives ($CaCl_2$) were acquired from Pascal Scientific Company. Additional tools consist of a 2 mm wire mesh sieve, a cold pressure press machine, a 350 mm by 350 mm wooden mould, an electric digital scale, plywood covering, and polythene.

Board formation

To get rid of any inhibiting chemicals, the bagasse was gathered, cleaned, and immersed in hot water for thirty minutes. After that, the bagasse was dried and ground into little pieces using a hammer. After being submerged in water for two days, the Kraft paper was ground using a milling machine.

The following were the production variables:

The mixing ratio of waste particles to cement of 2:1, 3:1, and 4:1 based on previous research findings to ensure appropriate variation (Ajayi, 2006). The elements listed below remained consistent while the board was being produced: 3% is the addictive concentration. 1200 kg/m^3 is the nominal board density. Simatupang's formula (1989) was used to determine the amount of water needed to dissolve the addictive substance.

$Wt = W (0.30-MC) + 0.60C$

Where

Wt= Water weight, W = Particle weight after drying in the oven., Mc stands for moisture content percentage (about 12%) and C stands for cement weight.

Mat formation

Using an electrical digital balance, the amount of cement and waste materials needed to produce each sample, along with its density of 1200 kg/m^3, were calculated and measured. The materials were then stored inside a small polythene bag based on the level of combination used in the experiment and labelled. Based on the percentage of cement (3% weight) used for each sample, the chemical additives were computed and weighed. The materials required to produce each sample were measured out, labelled, and poured into a plastic bowl. The necessary amount of additive was then dissolved in the necessary amount of water, and everything was thoroughly mixed by hand for bagasse and by using a milling machine for paper.

To facilitate quick de-moulding and prevent the board from sticking to the plate, a pre-made hardwood mould measuring 350 by 350 mm was set on a metal caul plate containing polythene sheets. The material was laid out on the plate, pre-pressed, and then moved to the cold press for 24 hours at 1.23 N/mm^2 of pressing pressure to form the necessary thickness of 8 mm. Following this, the boards were taken out of the press and allowed to cure for an additional 28 days. The previously mentioned procedures were used to produce all other boards (Ajayi, 2006). A total of 60 boards were produced for waste and bagasse boards

Plate 1: Production process of the boards

Board testing

Following the ASTM for particle board test, each test specimen was cut into the necessary sizes for each testing experiment and the board edges were trimmed using a circular saw to prevent edge effect. Physical and mechanical properties were determined in accordance with ASTM D 1037-06a and ASTM D 7519-11 standard

Thickness swelling

This was done by measuring the initial thickness (T1) with the use of a Vernier calliper before the test samples were soaked in water for 24 hours and the measurement of the final thickness (T2) after soaking. The thickness swelling was estimated using the formula

$$\text{Thickness swelling} = \frac{final\ thickness\ after\ soaking - initial\ thickness\ before\ soaking}{(initial\ thickness\ before\ soaking)} \times 100$$

Water absorption

This was done to determine the dimensional stability of the board produced, the boards were then submerged in distilled water for 24 hours after which the saturated weights of the samples were measured immediately after the given water absorption period. The board samples were then dried at a stable oven temperature of 103ºC and reweighed to obtain their oven dried weights. Thus, water absorption will be calculated with this scientific formula;

$$\%\ \text{Water Absorption} = \frac{W\_wet - W\_dry)}{W\_dry} \times 100$$

Flexural test

A total of 30 samples were used for this test. The modulus of rupture and modulus of elasticity were evaluated by subjecting a sample to a force or load on the universal tensiometer machine. The board was supported by the metal bearing plates to prevent damage to the beam at the point of contact between the board and the reaction support. The forward movement of the machine leads to the gradual increase of load at the middle of the span until failure of the test of the specimen occurs. At the point of failure, the force exacted on the specimen that caused the failure was recorded; Thus, MOE and MOR were evaluated using the formula below;

$$\text{MOE} = \frac{PL^3}{4bd^3H}$$

Where L is Span of board sample between the machine support (mm), B is the width of the board sample (mm), H is the thickness of the board sample (mm), p is the Ultimate failure load (N), and D is Deflection

$$\text{MOR} = \frac{3PL}{2BH^2}$$

Where L= Span of board sample between the machine support (mm), B is the Width of the test board (mm), H is the Thickness of the test board (mm) and P is the Ultimate failure load (N)

Plate 2: Physical and mechanical tests for boards

Data analysis

Data collected were subjected to analysis of variance (ANOVA) and the Duncan multiple range test.

Results and Discussion

The findings are as presented below.

Water absorption and thickness swelling

The mean values of water absorption varied from 25.60±0.29 to 39.02±0.97 %, whereas the mean values of thickness swelling varied from 1.75±0.31 to 6.11±1.18 %. The board's reaction to the water intake demonstrated that a drop in WA results from increasing the cement ratio from a 2:1 to a 4:1 mixing ratio. The greatest mixing ratio (4:1) produced the board with the lowest WA level, whereas the highest mixing ratio (2:1) produced the board with the highest WA level. The increase in cement proportion, which guarantees complete encapsulation of the fibres, is responsible for the decrease in water absorption. This aligns with Owoyemi *et al*. (2014) that observed that when the amount of cement was increased, a drop in WA occurred. The compatibility of the fibre and cement, which led to appropriate material consolidation, was another factor in the decrease in WA. Additionally, because the fibres were covered with cement, there is less water input and, as a result, less dimensional movement. In terms of WA and TS, boards made from paper board offered superior physical qualities. In contrast to boards made from paper, boards made from bagasse have inferior mechanical and physical qualities. The fluffy bagasse core that re-emerges after mat formation is less compatible with cement, which results in void areas in the boards. When water fills the vacuum spaces which are indicated by the formation of bubbles when submerged in it more moisture is taken in, which increases thickness swelling and moisture intake (Lin *et al*., 2023).

The maximum recommended water absorption by IS 14276 is 25% for 24 hours, the water absorption recorded for bagasse and paper is higher than this, therefore this material cannot be used in areas largely exposed to water. For thickness swelling, the

American National Standards Institute (A208.1-1999) stipulated that the maximum thickness swelling is 8%. Thus, all the specimens tested fulfilled the thickness swelling requirements.

Modulus of rupture (MOR) and modulus of elasticity (MOE)

The MOR and MOE mean values (Table 1) varied from 0.82±0.13 N/mm^2 to 2.05±0.62 N/mm^2 and from 271.53±33.30 N/mm^2 to 4154.97±199.13 N/mm^2 respectively. The results indicated that the MOE and MOR increased as the board's cement content increased and that this trend was also seen in boards made from waste paper. These results are consistent with previous study such as Ye *et al.* (2015), who found that an increase in the board's cement content improved the strength and dimensional properties of the board. Figures 1 and 2 demonstrated that the strongest boards were made at the highest level of the mixing ratio (4:1), which is consistent with a previous report (Pipíška *et al*., 2024). In contrast, the board made at the lowest level of the mixing ratio (2:1) has low strength, which is also supported by studies such as Han *et al*. (2023). According to Wang *et al*. (2016), increasing the amount of cement in the matrix can result in the production of board with high strength qualities. Bufalino *et al.* (2023) established that the addition of calcium chloride sped up the cement hydration and setting process and that the steady rise in all production variables involved in the manufacture of boards was responsible for the fabrication of stronger and heavier boards.

The results of the analysis of variance for MOR and MOE of the cement-bonded particle board made from bagasse and paper, which are displayed in Tables 2 and 3, indicate that the board's MOR and MOE were significantly influenced by the mixing ratio of particle to cement Tables 4 and 5 demonstrate that the mixing ratio had a major impact on water absorption. The board was significantly affected by the type of material for thickness swelling, while the mixing ratio had no discernible influence. The board's thickness swelling, and water absorption trend are depicted in Figures 1 and 2. Longer and more uniform fibres are what give the paper board its high-strength characteristics. Due to non-homogenous fibres from the inclusion of the fluffy core, which contains an element of sugar and prevents cement bonding, lower strength qualities were seen in bagasse (Xu *et al.* 2018).

The MOE of the boards produced was impacted by the combined effect of the type of material and the mixing ratio. The board with the highest mean value was created in the higher mixing ratio class (4:1). This is consistent with previous research by Ajayi (2006) and indicates that an increase in the proportion of the binder (cement) led to a corresponding increase in the MOE value. This demonstrates that, as noted by Owoyemi *et al*. (2014), producing boards with excellent strength qualities is possible when the cement fraction is raised. According to Figure 3, the strongest boards were produced at the highest mixing ratio (4:1), while the weakest boards were produced at 2:1 for both bagasse and waste paper. These results are consistent with an earlier report by Hwang and Oh (2020), which found that the strength properties of boards produced increase with increasing mixing ratio of the particles to binder.

Better mechanical strength in paper board generated at varying production levels is ascribed to lower extractive content in the paper, as extractive material is removed during pulping before papermaking. Additionally, residual inhibitory chemicals are removed during paper recycling, improving the paper's ability to establish a covalent bond with cement. The inner core's presence of sugar, which prevents cement hydration and delays setting and curing, maybe the cause of the boards made from bagasse's low strength characteristics (Karade, 2016). Particle Board made from paper had the peak MOR value of 9.07N/mm^2 and the least MOR of 4.74N/mm^2, while bagasse Particle Board made from paper had the peak MOR value of 2.05N/mm^2 and the least MOR of 0.82N/mm^2 for bagasse. These values are above the minimum standard of 3 N/mm^2 specified by the American National Standards Institute (A208.1-1999) for paper boards alone while it is not so for bagasse and this makes it suitable for general purpose particle boards. This is also in the same range as the values reported by (Atoyebi *et al., 2018*; Zhou *et al*., 2002; Ajayi & Badejo, 2005; Aladejana & Oluyege, 2016) for particle boards produced from some other composite materials. Paper had the maximum MOE of 4154.97N/mm^2 and the lowest value of 2173.93 N/mm^2 while bagasse had a maximum MOE of 486.06 N/mm^2 and least of 271.53N/mm^2. Ghaffar *et al.* (2018); Aisien *et al.* (2015); A208.1-1999 reported that the minimum allowable MOE for particle boards is 550 N/mm^2. Particle boards made from bagasse fall below this standard while paper board particle board is above this standard which indicates that paper has higher strength than bagasse boards. Values in Table 1 represent mean ± standard error

Table 1: Mean values of MOE, MOR, TS, and WA for bagasse and paper boards

Mixing ratio	Waste material	MOE(N/mm^2)	MOR(N/mm^2)	TS (%)	WA (%)
2:1	Bagasse	271.53±3.30	0.82±0.13	6.11±1.18	35.56±0.59
	Waste Paper	2173.93±6.03	4.74±0.40	2.24±0.42	39.02±0.97
3:1	Bagasse	341.41±4.72	1.12±0.18	5.83±0.42	29.42±0.61
	Waste Paper	2640.83±5.62	5.11±0.58	2.02±0.17	33.97±3.45
4:1	Bagasse	486.06±3.78	2.05±0.62	4.86±0.85	28.30±2.39
	Waste paper	4154.97±9.13	9.07±0.50	1.75±0.31	25.60±0.29

Table 2: Analysis of variance for MOR for bagasse and paper boards

Source	Sum of Squares	Df	Mean Square	F	P
Mixing ratio	11.63	2	5.816	9.86	0.003*
Waste material	111.40	1	111.40	188.80	0.00*
Interaction	25.44	2	12.72	21.56	0.00*
Error	7.08	12	0.59		
Total	155.56	17			

* = (P<0.05) are significant, ns = Not significant (P>0.05)

Table 3: Analysis of variance for MOE for bagasse and paper boards

Source	Sum of Squares	Df	Mean Square	F	P
Mixing ratio	2857728.53	2	1428864.27	17.47	0.00*
Waste material	30974221.60	1	30974221.60	378.64	0.00*
Interaction	3649186.96	2	1824593.48	22.30	0.00*
Error	981650.12	12	81804.18		
Total	38462787.21	17			

* = (P<0.05) are significant, ns = Not significant (P>0.05)

Table 4: Analysis of variance for WA for bagasse and paper boards

Source	Sum of Squares	Df	Mean Square	F	P
Mixing ratio	228.40	2	114.20	11.81	0.01*
Waste material	35.93	1	35.93	3.72	0.78ns
Interaction	117.02	2	58.51	6.05	0.015ns
Error	116.01	12	9.67		
Total	497.36	17			

* = (P<0.05) are significant, ns = Not significant (P>0.05)

Table 5: Analysis of variance for TS for bagasse and paper boards

Source	Sum of Squares	Df	Mean Square	F	P
Mixing ratio	0.57	2	.28	0.219	0.807ns
Waste material	58.21	1	58.21	44.91	0.000*
Interaction	2.39	2	1.20	0.92	0.424ns
Error	15.55	12	1.30		
Total	76.72	17			

* = (P<0.05) are significant, ns = Not significant (P>0.05)

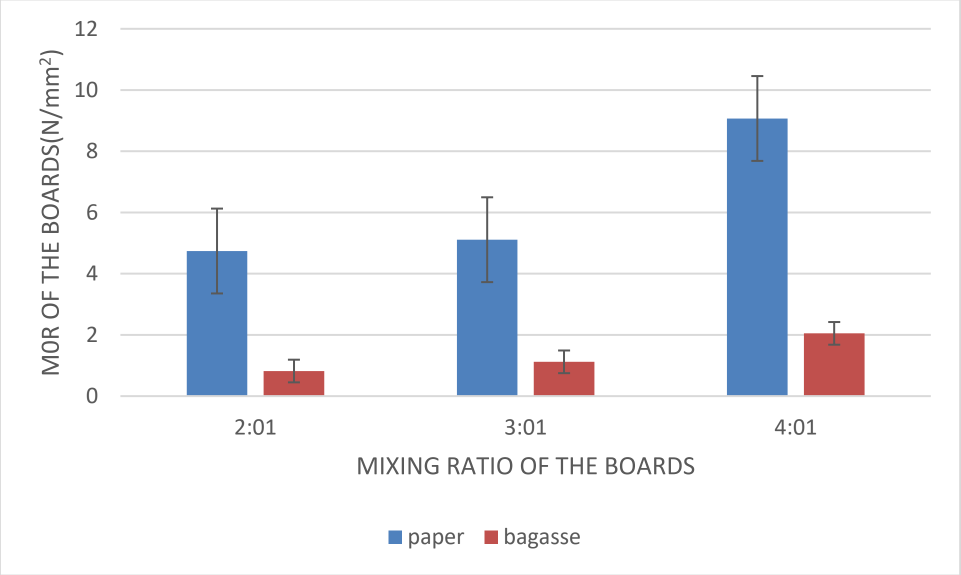

Figure 1: Effect of mixing ratio on MOR of boards showing an increasing trend of MOR as Mixing ratio increases

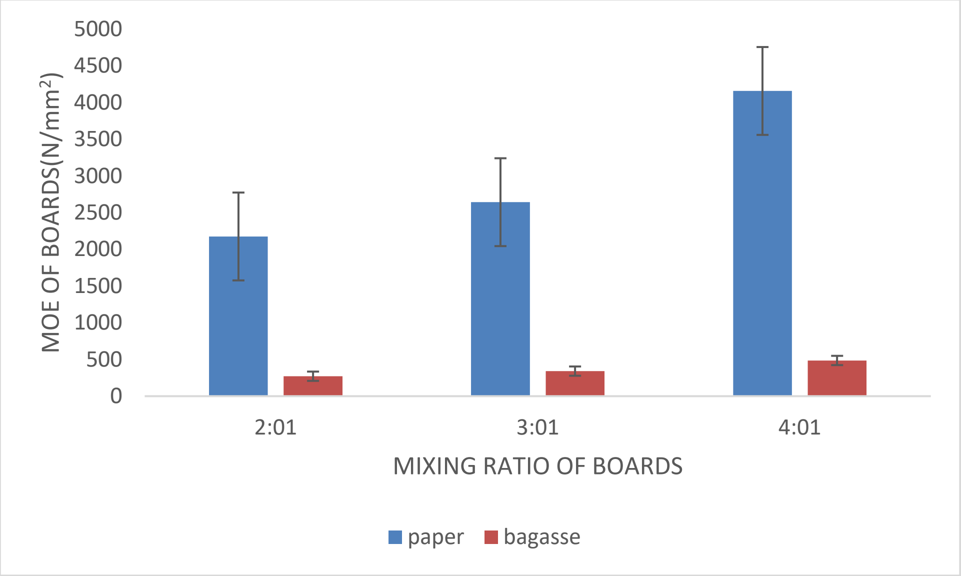

Figure 2: Effect of mixing ratio on MOE of the boards showing an increasing trend of MOE as mixing ratio increases

Conclusion

Paper and bagasse were the two materials used to make cement-bonded boards. Boards made from bagasse have a higher thickness swelling, lower water absorption, lower modulus of rupture, and lower modulus of elasticity than boards made from paper. The boards were manufactured at three different mixing ratios: 2:1, 3:1, and 4:1. At the maximum 4:1 mixing ratio, boards made from both paper and bagasse exhibited greater dimensional stability and strength. Because paper has a uniform structure and long fibres, boards made of it have greater strength qualities and dimensional stability. Unfortunately, because bagasse contains a fluffy core that causes the board to spring back after being pressed, leaving a gap in the board, bagasse boards are not as strong. The manufacturing of cement-bonded composite boards using bagasse and paper may help reduce environmental contamination, which is brought on by the disposal of these waste materials. Furthermore, it promotes trash recycling as a preventive measure against ozone layer depletion caused by greenhouse gas emissions from burning bagasse and paper. Due to high water absorption properties, the boards produced from bagasse and waste paper have been found suitable for structural purposes for non-exterior works. Therefore, further studies should be done on lesser-explored waste materials and tested under different weather conditions to ascertain their suitability in this environment. Bagasse boards should be reinforced with other materials such as papers and fibres to ensure enhanced properties for different applications.

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