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Use of *Agave durangensis* Bagasse Fibers in the Production of Wood-Based Medium Density Fiberboard (MDF)

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Abstract: There is an increasing interest in using non-wood lignocellulosic materials for the production of wood-based medium density fiberboard (MDF). *Agave durangensis* Gentry bagasse is a waste product produced in large quantities in the mezcal industry. This study evaluated the incorporation of *A. durangensis* bagasse fibers (ADBF) to elaborate MDF wood-based panels. Three types of panels with different ratios (wood fibers: bagasse fibers) were investigated. The ratios evaluated were 100:0, 90:10, and 70:30. The density profiles, water absorption, and thickness swell of the panels were determined, as well as the modulus of elasticity (MOE), modulus of rupture (MOR), and internal bond (IB), according to the ASTM D1037-06a standard. The results were compared to the ANSI A208.2-2016 standard. The effect of the addition of ADBF on the properties of the panels was analyzed. Density profiles were comparable among the three types of panels, while water absorption, thickness swelling, MOE, MOR, and IB were similar between panels with ratios of 100:0 and 90:10. Panels with 10% and 30% of ADBF meet the minimum ANSI requirements for quality grade 115. It is feasible to use up to 30% of ADBF in the manufacture of wood-based MDF panels.

Keywords: non-wood fibers; MOE; MOR; internal bond; thickness swell; water absorption; density

1. Introduction

The demand for wood-based panels is increasing rapidly year after year. Fiberboards are among the panels that are increasingly in demand. According to ANSI A208.2-2016, medium density fiberboard (MDF) is recognized as a fiberboard panel of density between 500 and 1000 kg·m^{-3} [1]. Medium density fiberboard is a panel composed of cellulosic fibers bonded with resin under heat and pressure. Medium density fiberboards have a wide application for non-structural uses [2], such as in the home and office furniture markets [3]. There are many advantages that distinguish MDF from other panels including edge screwing, painting properties, and good machining [4].

Wood is commonly used as raw material for the manufacture of MDF [5]. However, the increasing demand for forest resources for different uses has led to the shortage of wood supply. Therefore, the supply of raw material cannot meet the demand of the wood industry in many regions of the world [6,7]. This is why it is necessary to search for new lignocellulosic materials that may help to fulfill the requirements of the forest products industry [8–10]. These alternative lignocellulosic materials comprise forest harvesting residues such as bark, annual plants, residues from wood products and furniture industries, residues from pulp mills, and recycled paper [6]. However, non-wood fiber has acquired great relevance as a sustainable natural fiber resource for composite products. The use of agricultural fibers as composite panel material is common in many parts of the planet [2]. There is interest in agricultural residues, which are generated on a large scale worldwide [9].

In recent years, the use of various non-woody fibers in the production of MDF panels have been studied. Rhododendron [6], canola [11] and wheat straw [5], kenaf [12], oil palm stem [13], coffee bean residues [14], banana leaf stem and lamina [15], okra [8], sugarcane bagasse [4], sunflower and corn stalk [16], and hemp [17] were considered, among others. However, there are still several fibers that have not been used in the production of wood-based MDF, including bagasse from *Agave durangensis* Gentry.

Agave bagasse is the waste that remains after the boiled agave heads are shredded and ground and the sugars are removed with water. Bagasse fibers could be used to elaborate a broad variety of products such as filters, absorbents, geotextiles, fiberboard, packaging, and molded products [18]. When one liter of mezcal is produced, it generates 15 to 20 kg of bagasse [19]. In 2019, 178,625 L of mezcal were produced in the state of Durango, Mexico [20]. That year, it is estimated that 2679 to 3572 tons of wet base agave bagasse were produced [21]. The objective of this work was to determine the effect of *A. durangensis* bagasse fibers on the physical and mechanical properties of wood-based MDF panels.

2. Materials and Methods

2.1. Materials

For this work, *A. durangensis* bagasse fibers (ADBF) and wood fibers (WF) were used to manufacture the panels. The ADBF was donated by Productora de mezcal Hacienda Dolores located in Durango, Dgo, Mexico. The WF were a mixture of spruce, fir, and pine and were donated by the Uniboard plant company located in Mont-Laurier, Quebec, Canada. The adhesive used was urea formaldehyde (UF) (Table 1) donated by Hexion located in St. Romuald, Quebec, Canada.

Table 1. Properties of urea formaldehyde adhesive.

Properties	Unit	Value
Appearance		Clear to white liquid
Solids content	(%)	67.00 ± 1.00
Specific Gravity	(kg·m^{-3})	1.305 ± 0.010
Viscosity	cPs	335 ± 75
pH @ 25 °C		8.20 ± 0.20
Buffer capacity	mL	11.5 ± 3.0
Storage life 25 °C (77 °F)	Days	21

2.2. Manufacture of MDF Panels

The panels were produced at the Composite Panel Laboratory of the Department of Wood and Forest Sciences at Université Laval in Québec, QC, Canada. Three replicates of each panel type were produced for this study (Table 2).

Table 2. Types of panels and their ratios of raw material used.

Type of Panel	Raw Material (%)	
	Wood Fibers (WF)	*A. durangensis* Bagasse Fibers (ADBF)
MDFC	100	0
MDF10	90	10
MDF30	70	30

MDFC: Medium-density fiberboard manufactured with 100% of WF; MDF10: Medium density fiberboard produced with 90% of WF and 10% of ADBF; MDF30: Medium density fiberboard elaborated with 70% of WF and 30% of ADBF.

The adhesive and wax were applied to the fiber in a rotary drum blender, using 14% resin and 1% wax (by weight of the dry fiber), and NH_4Cl at 25% catalyst was added to the resin to lower its pH. Once the furnish was formed, it was taken through a ring refiner (Pallman PSKM8-450) to separate the fiber aggregates formed during blending in the drum. The fiber mat was formed using the refined furnish. It was carried out manually using a wooden mold with the dimensions established for the board. The formed mat was pre-pressed before hot pressing. The hot pressing was performed in a Dieffenbacher hot press. The panels had dimensions of 760 by 760 mm, a target thickness of 12 mm, and a target density of 700 $kg \cdot m^{-3}$.

2.3. Physical and Mechanical Properties of MDF Panels

The vertical density profile of the manufactured MDF panels was determined using a Quintek X-Ray densimeter (QMS Core Model QPRS-01x and QMS Particleboard Model QDP-01x). The physical and mechanical properties of the panels were determined according to ASTM D1037-06a [22] and ANSI A208.2-2016 [1]. The physical properties evaluated were water absorption and thickness swell at 2 and 24 h, while the mechanical properties determined were internal bond (IB), modulus of elasticity (MOE), and modulus of rupture (MOR). The number of specimens for each test and their characteristics are shown in Table 3. The specimens used for the density profile were the same as those used in the IB tests. The specimens were conditioned for 15 days at 65% relative humidity and 22 °C. The mechanical tests were carried out in an MTS universal mechanical testing machine with a capacity of 5 kN.

Table 3. Tests and samples sizes and number. The samples used for WA2h, WA24h, TS2h, and TS24h tests were the same.

Test	Symbol	Size (mm)	Samples per Panel	Samples per Type of Panel
Water absorption after 2 h	WA2h	150 × 150	4	12
Water absorption after 24 h	WA2h			
Thickness swell 2 h	TS2h			
Thickness swell 24 h	TS24h			
Internal bond	IB	50 × 50	6	18
Modulus of elasticity	MOE	75 × 339	6	18
Modulus of rupture	MOR			

2.4. Statistical Analysis

Completely randomized design was used to analyze the data for each variable. Data were analyzed using R Studio software [23]. A Shapiro–Wilk test was used to analyze the normality of data. Analysis of variance (ANOVA) ($p \leq 0.05$) and comparison of means with Tukey test were performed. Furthermore, Pearson correlation analyses were performed between average density, and water absorption and thickness swell. Additionally, Pearson correlation analyses were performed between internal cohesion and average, maximum, and minimum densities.

3. Results and Discussion

3.1. Panels Density

The density profiles for the three types of MDF panels are presented in Figure 1. It shows a higher density near the surfaces, while the center of the panels presented a decrease in density. According to Halvarsson et al. [24], in MDF panels with this type of density profile, it is the more compressed fibers of the high-density surface layers that expand the most when the MDF samples are immersed in water for 24 h, thus causing swelling. The panels with 10 and 30% of ADBF presented a similar density profile to the WF panel (Figure 1A). However, there is a minimal difference between the profiles, which may be caused by the ADBF; therefore, it is likely that this small difference influences the properties of these panels. The density profile is related to the performance of the panel. A deep density profile allows the board to better laminate, glue, and finish due to the high density of the surface [25]. On the other hand, when the density profile is more flat, it can reduce the bending properties of the panels [26].

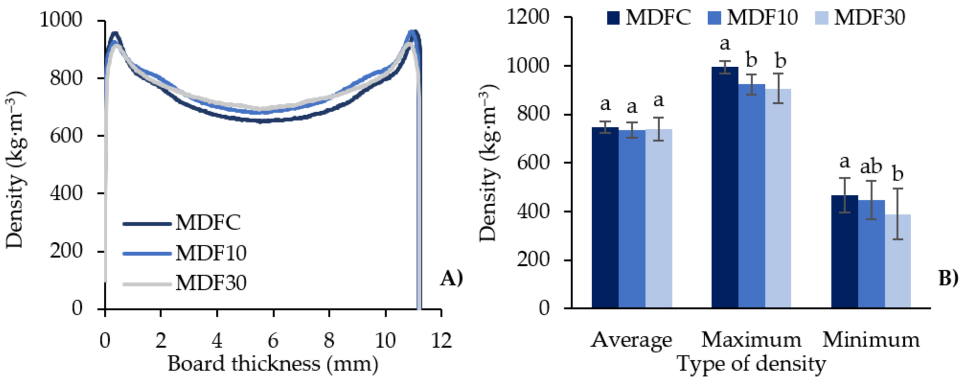

Figure 1. Density of MDF panels. (**A**) Density profiles of the average of eight samples of MDF panels. (**B**) Types of density of the panels obtained from the X-ray densitometry. Different lowercase letters represent statistically significant difference among panels by Tukey test ($p \leq 0.05$).

The highest average density was obtained for MDFC (749 $kg \cdot m^{-3}$), followed by MDF30 (738 $kg \cdot m^{-3}$) and MDF10 (735 $kg \cdot m^{-3}$). The higher maximum density was obtained by MDFC (995 $kg \cdot m^{-3}$), while the minimum density was obtained for MDF30 (390 $kg \cdot m^{-3}$). There are no statistically significant differences between the three types of panels in the average, but there are for the maximum density, with MDFC being different from MDF10 and MDF30, while for the minimum density, MDFC showed a significant difference with MDF30 (Figure 1B). The p value of the ANOVA test for average, maximum, and minimum density of the panels is shown in Table 4. Panels did not present statistically significant difference in average density, while in maximum and minimum densities, there was significant difference.

Table 4. *p* value of ANOVA test for average, maximum, and minimum density of the panels.

Type of Density	*p* Value
Average	0.4565
Maximum	3.08×10^{-7}*
Minimum	0.0268*

* Statistically significant difference for $p \leq 0.05$.

3.2. Water Absorption and Thickness Swell

Water absorption and thickness swelling after 2 and 24 h in water immersion are shown in Figure 2. The lowest water absorption (Figure 2A) at 2 and 24 h was obtained for MDFC (3.7% and 18.9%, respectively), while MDF30 had the highest absorption at 2 (4.7%) and 24 h (22.4%). There were no significant differences between MDFC and MDF10 in water absorption at 2 and 24 h; however, there were significant differences between these and MDF30. The lowest thickness swelling (Figure 2B) was presented by MDFC at both 2 (0.9%) and 24 h (4.5%), followed by MDF10 (1.1% and 4.9%, respectively). There were no statistically significant differences between MDF10 and the other panels for thickness swell at 2 h, but there was between MDFC and MDF30. Statistically significant differences were found between the three types of panels in thickness swell at 24 h.

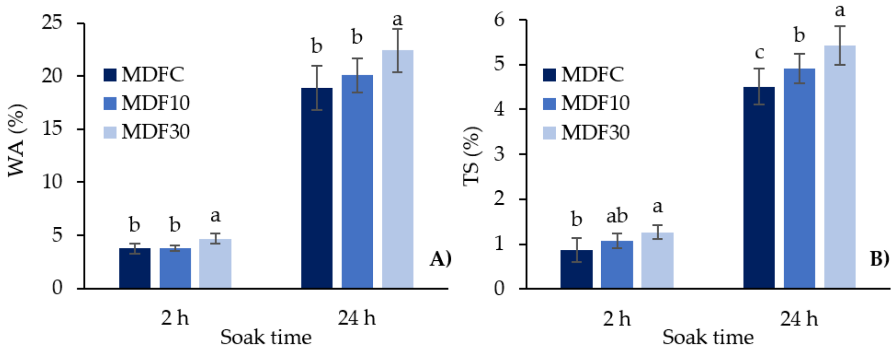

Figure 2. Dimensional stability. (**A**) Water absorption after 2 and 24 h of submersion of MDF panels. (**B**) Thickness swelling after 2 and 24 h of submersion of MDF panels. Different lowercase letters represent statistically significant difference among panels by Tukey test ($p \leq 0.05$).

Table 5 shows the *p* value of ANOVA test for WA and TS after 2 and 24 h in water immersion of the panels. The panels presented statistically significant difference in WA and TS, both at 2 and 24 h.

Table 5. *p* value of ANOVA for WA and TS at 2 and 24 h of submersion of the panels.

Property	*p* Value
WA2h	1.29×10^{-6}*
WA24h	0.000269*
TS2h	0.000162*
TS24h	1.05×10^{-5}*

* Statistically significant difference for $p \leq 0.05$.

The results indicate that ADBF decreases the resistance of the panels to water absorption and swelling in thickness. According to Moreno-Anguiano et al. [21], fiber of bagasse of *A. durangensis* contains 32.4% extractives, 44.7% holocellulose, 7.6% lignin, and 12.6% ash. Thus, the high content of extractives present in ADBF could have caused poor gluing of these fibers, due to the migration of extractives to the surface after high pressing temperatures [27]. On the other hand, Xing et al. [10] stated that excessive curing of the UF resin in the surface layers of the panel may also have caused high thickness swelling. In addition, agricultural residues have a higher buffer capacity compared to wood [28]. These aspects remain to be investigated further.

Water absorption is a property of panels related to their dimensional stability, which has been studied by several authors. Despite water absorption is reported in the literature, it is not a characteristic evaluated in the ANSI A208.2-2016 standard. The results obtained for WA in MDF10 and MDF30 panels are lower than those reported by Akgül [29] for MDF made with 10–90%, and 30–70% of *Urtica dioica* L. stem-wood fiber, respectively. Akgül [29] indicates that the addition of *Urtica dioica* stem fiber to the panels reduced their physical properties; nonetheless, they still met the standards. Similarly, MDF30 showed lower WA than those obtained by Akgül and Tozluoğlu [30] on MDF from *Arachis hypogaea* L. husk and wood fibers. These authors report that *Arachis hypogea* husk could be added up to 30% for the production of MDF.

The TS values obtained are lower than those reported by other authors for panels made from wood and non-wood fiber [31–33]. Lee et al. [31] evaluated MDF manufactured from blends of sugar cane bagasse and tallow tree fibers. They found that the maximum percentage to manufacture MDF is 50% without impact on thickness swelling. Whereas Akgül et al. [32] produced MDF with mixtures of pine wood and corn stalks, and they mentioned that the addition of corn stalks reduced the panel properties.

The TS (expressed in mm) at 2 and 24 h of immersion is plotted as a function of average density in Figure 3. The TS values presented by the panels meets the maximum required by ANSI A208.2-2016 for medium density fiberboard.

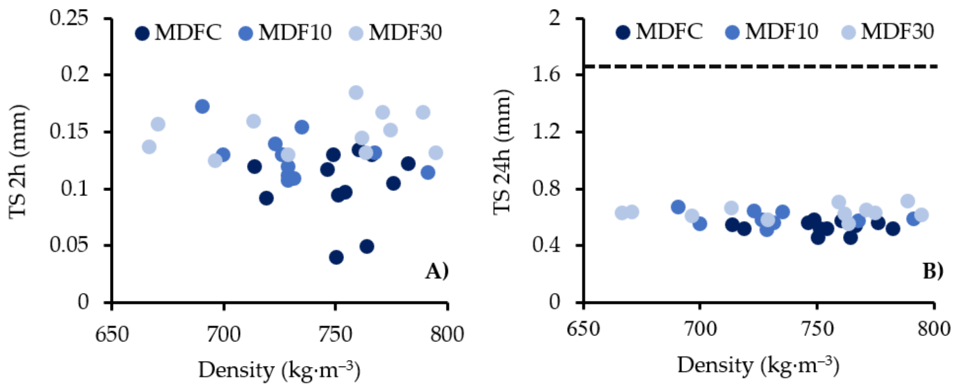

Figure 3. Thickness swell as function of density of MDF panels. (**A**) Thickness swell after 2 h as a function of density of MDF panels. (**B**) Thickness swell after 24 h as a function of density of MDF panels. The dotted line represents the maximum TS for panels < 15 mm according to ANSI A208.2-2016.

The Pearson correlation among average density values and water absorption and thickness swelling is presented in Table 6. There is a significant correlation between the average density of MDF30 and water absorption after 24 h, which is a strong positive correlation. On the other hand, there is no significant correlation between the rest of the variables.

Table 6. Pearson correlation for average density values and water absorption and thickness swelling of MDF panels.

		WA2h	WA24h	TS2h	TS24h
MDFC	Correlation	−0.3007	−0.1049	0.2098	0.1049
	Significance	0.34	0.75	0.51	0.75
MDF10	Correlation	−0.0403	0.2134	−0.4775	−0.312
	Significance	0.90	0.51	0.12	0.32
MDF30	Correlation	0.5412	0.6124 *	0.3434	0.3272
	Significance	0.07	0.03	0.27	0.30

* Significant correlation ($p \leq 0.05$).

3.3. Internal Bond

Internal bond was higher in MDFC (0.84 N·mm^{-2}), while the lowest resistance was presented by MDF30 (0.70 N·mm^{-2}). MDF10 had an internal bond of 0.83 N·mm^{-2}. There are no statistically significant differences between MDF10 and MDFC; similarly, there are no significant differences between MDFC and MDF30. The presence of 10% ADBF does not affect the internal bonding strength with respect to MDFC panels; however, increasing the percentage of ADBF to 30 decreases. The internal bonding strength showed by the panels with ADBF meets the minimum required by ANSI A208.2-2016. The MDF10 panels reach grade 155 while MDF30 meets grade 130 (Figure 4).

The results obtained for IB are higher than those reported by other authors for panels with similar proportions of wood fiber and non-wood fiber. Gillah et al. [34] reported an IB of 0.48 N·mm^{-2} for sisal and wood fiber panels, in which their IB was reduced with the addition of sisal fibers. Abdul et al. [35] indicated an IB of 0.73 N·mm^{-2} for oil palm empty fruit bunch and rubber wood panels. They also reported that the increase of non-wood fibers into the panels decreased their properties. On the other hand, Belini et al. [36] obtained an IB of 0.58 N·mm^{-2} for eucalyptus and bagasse fiber panels with a ratio of 75:25%. Nevertheless, the IB increased to 0.80 N·mm^{-2} when a ratio of 50:50% was used.

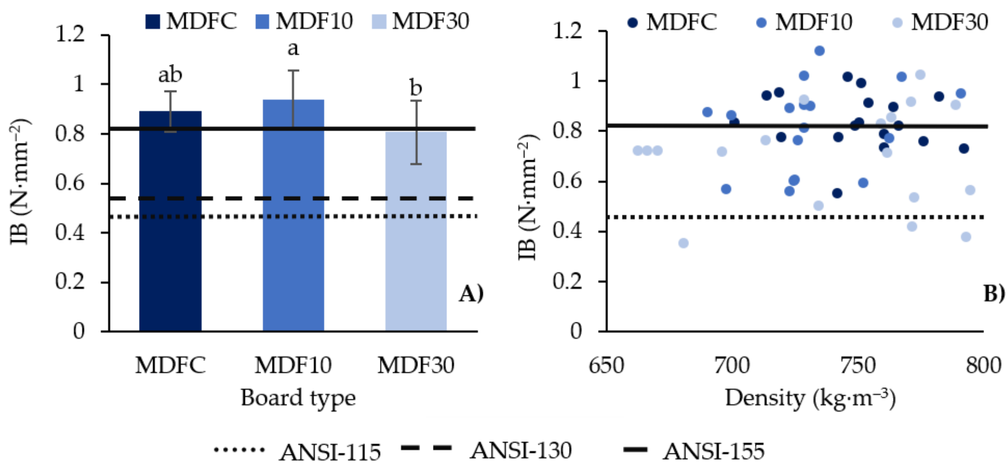

Figure 4. Internal bond of MDF panels (**A**) Internal bond of MDF panels. Different lowercase letters represent statistically significant difference among panels by Tukey test ($p \leq 0.05$). p value of ANOVA for internal bond is 0.0195. (**B**) Internal bond as a function of density of MDF panels. Lines represent MDF standard requirement for 115, 130, and 155 grades according to ANSI A208.2-2016.

The decrease of IB in MDF30 panels may be caused by the high presence of extractives in bagasse fibers. Regularly, extractives modify the properties of lignocellulosic materials, which, in turn, alters their adhesion properties [37]. It is possible that the waxes in the bagasse fibers are incompatible with phenolic resins because of their different polarities. Thus, the adhesive decreases its ability to penetrate the lignocellulosic material, resulting in a lower resistance to internal bond of the panels [38].

Table 7 shows the Pearson correlation between internal bond and the different densities obtained in the X-ray densitometer. Neither of the MDF panels presented significant correlations between internal cohesion and average, maximum and minimum density.

Table 7. Pearson correlation for different density values and internal bond of MDF panels.

Test		Average Density	Maximum Density	Minimum Density
MDFC	Correlation	−0.149	0.027	0.181
	Significance	0.56	0.91	0.47
MDF10	Correlation	0.425	0.290	0.286
	Significance	0.08	0.24	0.25
MDF30	Correlation	−0.005	0.147	0.234
	Significance	0.98	0.56	0.35

Significant correlation ($p \leq 0.05$).

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

Figure 5 shows the values of the modulus of elasticity and modulus of rupture obtained for each type of board. MDFC panels presented the highest MOE (1955 N·mm^{-2}); nevertheless, there is no significant difference between them and MDF10 (1786 N·mm^{-2}). On the other hand, MDF30 panels had the lowest MOE (1526 N·mm^{-2}), which was significantly different from MDFC and MDF10 (Figure 5A). Regarding the MOR, the highest average value was shown by MDFC (17.8 N·mm^{-2}), followed by MDF10 (17.6 N·mm^{-2}); however, there were no significant differences between them. On the other hand, MDF30 panels obtained the lowest value (13.2 N·mm^{-2}) and were significantly different from MDFC and MDF10 (Figure 5B). The MOE and MOR values are lower than those reported by other authors for processed wood fiber and non-wood fibers MDF panels using fiber ratios similar to this work. Çöpür et al. [39] report MOE of 2320 and 2852 N·mm^{-2} and MOR of 18.6 N·mm^{-2} for panels made from hazelnut shells and fibers of *Pinus nigra* and *Fagus orientalis*. They stated that up to 20% of hazelnut shells could be utilized to manufacture panels which meet the standards. Akgül et al. [40] indicate MOE of 4035 N·mm^{-2} and MOR of 27.1 N·mm^{-2} in corn stalk and oak wood panels. In their case, the incorporation of corn stalk did not increase the MOE and MOR of the panels. Although the MOE and MOR of the present work were lower than other reported, MDF10 and MDF30 panels met the minimum value required by ANSI A208.2-2016 in MOE and MOR for grade 115 panels.

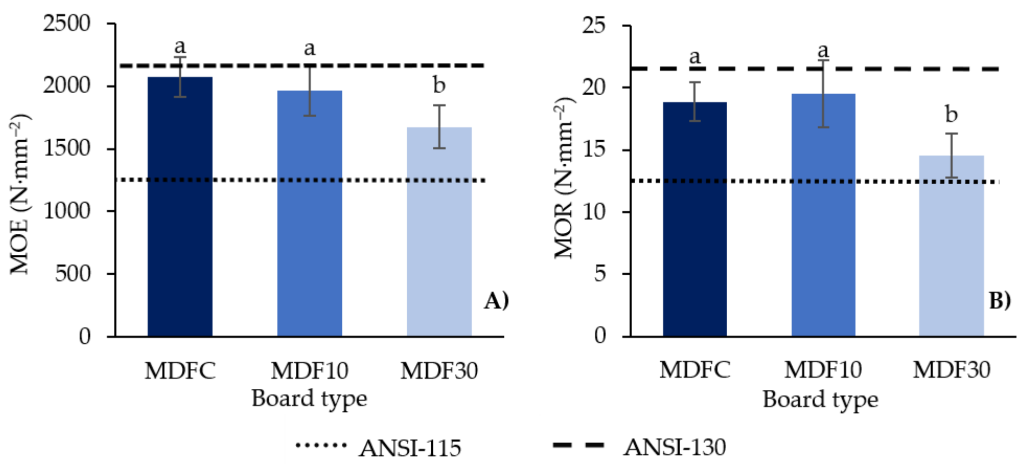

Figure 5. (**A**) Modulus of elasticity of MDF panels. *p* value of ANOVA for modulus of elasticity is 9.84×10^{-5}. (**B**) Modulus of rupture of MDF panels. *p* value of ANOVA for modulus of rupture is 6.50×10^{-6}. Different lowercase letters represent statistically significant difference among panels by Tukey test ($p \leq 0.05$). Dotted lines represent MDF standard requirement for 115 and 130 grades according to ANSI A208.2-2016.

The decrease in mechanical properties of MDF30 panels may be due to the presence of small particles in the ADBF and the minimal contact between them [33]. The pH of the ADBF is another factor that could reduce the mechanical strength of the panels. Moreno et al. [21] report that *A. durangensis* bagasse fiber has a pH of 5.8. According to Baharoglu et al. [41], materials with low pH result in panels with low strength properties, because adhesive curing occurs before hot pressing when the pH of the fibers is low [42]. When fibers with lower pH and UF resin are used in the MDF industry, it is expected to result in a higher degree of pre-curing during drying [43]. Nevertheless, UF is an adhesive that cures better in an acidic environment [44]. The aforementioned is in agreement with the results obtained by Park et al. [45], who reported that high alkalinity fibers retarded the curing of UF in MDF. According to Stefke and Dunky [46], the condensation reactions of UF resin take place during the hardening process causing a cross-linked condition and thus developing the internal bond between the fibers. UF preferably needs a low pH for the above to take place.

4. Conclusions

The results show that the incorporation of *A. durangensis* bagasse fiber does not affect the physical and mechanical properties of wood-based MDF panels. The MDF panels made with 10% of ADBF did not present significant differences in their physical and mechanical properties with the wood-based panels, except for the thickness swelling after 24 h. In contrast, panels with 30% ADBF showed significant differences from wood fiber panels. However, both panels with 10% and 30% of ADBF meet the requirements of grade 115 for medium density fiberboard for interior applications according to the American National Standard. Density did not correlate concerning water absorption and thickness swelling, except for the MDF30 board after 24 h. The densities did not present correlation with internal bonding. The addition of ADBF to panels did not affect the type of density profile of panels; however, the ADBF reduced the density of the MDF panels. These findings demonstrate the potential of *A. durangensis* bagasse fiber to be used as a complement in the manufacture of wood-based MDF panels.

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