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Physico-mechanical comparison of urea formaldehyde bonded particle board manufactured from jute sticks and wood of *Trewia nudiflora*

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Abstract. This study is to know the physical and mechanical properties of particle board made up of jute sticks (jutex board) and wood chips (woodex board) of *Trewia nudiflora*. Two leading particle board manufacturing industries of Bangladesh were selected first which have the same manufacturing process and adhesive composition. Boards of available thicknesses were collected randomly. From each thickness category, three replications were taken. The parameters were studied as adhesive composition, mass of a board, density, bending strength, modulus of elasticity, surface soundness, tensile strength, screw withdrawal, pressure and pressing time. Urea formaldehyde resin is used to manufacture both types of particle board. For achieving the greater efficiency of boards, some chemical compounds were mixed with the resin. Due to the change in thicknesses, boards were not always different in terms of the physical and mechanical properties. Moreover, except the modulus of elasticity (MOE), woodex boards were superior to the properties of jutex boards.
Keywords Jute particle board, wood particle board, physical & mechanical comparison.

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Introduction

The rising expectations and improving living standards of the developing countries, especially in Asia, seems certain to increase wood use (Sutton 1993). As observed by Alma et al. (2004), the world population currently consumes over 3.5 billion tons of green wood annually. If the consumption rate of wood fiber and the rate of population growth stay constant, the demand for wood fiber will increase by over 60 million tones each year. That would significantly increase deforestation, creating a huge negative impact on the environment

(Zheng et al. 2006). Kozlowski & Helwig (1998) reported that the particleboard industry supplied a significant portion of total wood consumption in the world, which was 0.36 billion cubic meters and expected to reach 0.47 billion cubic meters by the year 2010.

Traditionally, particleboard has been made out of wood-based fibers bound together using a formaldehyde resin. The desired thickness is achieved by using a hot press that forms the board into sheets (ABDP 2005). Particleboard has a homogenous structure and can be manufactured in different sizes, thickness, densities and grades for numerous uses, making it a desirable material with which to work (Strategis 2003). This type of board is a structural material made of wood fragments, such as chips or shavings, which are mechanically pressed into sheet form and bonded together with resin (Anon 2000). Other definition of particleboard is panel from dry wood particles that have been sprayed or dusted with a binder resin, and are bonded together with resin and heat (Charles 1986). Particles for the particleboards can be made from almost any type of wood, whether whole logs or log residues such as trimmings and shavings from lumber or plywood manufacturing (Charles 1986).

The particle board panel is often modified to many high-value products for different situations of usages such as fire-retardant treated particle board (for fire protection purposes), moisture resistant particle board (for outdoor use), thin particle board (for furniture industry), high density particle board (for flooring). The fire resistance of the composite is very important nowadays, especially when the composite is used as structural components. The primary objective of a fire-resistant structural design is to maintain the structural integrity during a fire for a sufficient period so that all the occupants may safely evacuate, firemen may extinguish the fire, and the loss of property may be minimized (Park et al. 2004). According to Rashid et al. (1990), particleboard is a combustible material. Previous studies revealed that treating particleboards with flame retardants were effective to reduce the combustibility and heat release of the panel (Rashid & Chew 1990, Izran et al. 2009). Particleboard is widely used in furniture, where it is typically overlaid with other materials for decorative purposes. It is the predominant material used in ready-to-assemble furniture. Particleboard can also be used in flooring systems, in manufactured houses, and as underlayment. Thin panels can also be used as a paneling substrate. Since most applications are interior, particleboard is usually bonded with a UF resin, although PF and MF resins are sometimes used for applications requiring more moisture resistance (Stark et. al. undated). The demand for glued-wood composite products, such as particleboard, medium-density fibreboard and plywood, has recently increased dramatically throughout the world, especially for housing construction and furniture manufacturing (Youngquist 1999, Sellers 2000). According to Drake (1995), particleboard consumption in the world represents 57% of the total volume of solid wood panel product consumption. Worldwide demand for particleboard has been growing steadily at a rate between 2 to 5% per annum (ANU Forest Market Report 2002).

Particleboard is readily made from virtually any wood material and from a variety of agricultural residues. Low-density insulating or sound-absorbing particleboard can be made from kenaf core or jute stick. Low-, medium-, and high-density panels can be produced with cereal straw, which has been used in North America. Rice husks are commercially manufactured into medium- and high-density products in the Middle East (Stark et. al. undated). Wood based particleboard is one of the panel products which can be manufactured from low quality trees, mill residue and agricultural materials such as wheat, or rice straw (Basturk 1993, Cai et. al. 2004). Using of traditional raw materials for composite panel manufacture is not playing a significant role in the commercial market in developed countries. However, the quality of lumber is dropping with unstable prices in many developing and underdeveloped countries and future supplies may also be very limited in such countries. Consequently, increasing environmental awareness has focused research on the exploration of new renewable raw materials such as agricultural waste (Kittisiri 1996).

In Bangladesh particle boards are manufactured using jute sticks and wood. The board which is from jute sticks is named Jutex and similarly boards from wood particles are termed as Woodex. In the woodex board the Pitali (*Trewia nudiflora*) was the raw material for chips. This study is to know the physical and mechanical properties of jutex and woodex particle board. The physico-mechanical properties of particle boards are an indication of quality and suitability in relation to the proposed use of the board (Cook et. al. 2000).

Material and methods

Experimental layout. Some particle board manufacturing industries of Bangladesh were selected first which have same or similar manufacturing process and adhesive composition. Two leading companies were found under that criterion. Boards of available thicknesses were collected randomly. From each thickness category, three replications were taken. The available boards of jutex were 12 mm, 18 mm, 25 mm, 30 mm, 36 mm and 41 mm and the available types of woodex boards were 12 mm, 16 mm, 18 mm and 25 mm.

Measurement and statistical analysis of data. The parameters mass of a board, density, bending strength, modulus of elasticity, surface soundness, tensile strength, screw withdrawal were measured by using the IMAL (IB 600) universal testing machine. Samples were taken according to the IMAL (IB 600) standard. Digital moisture meter was used to measure the moisture of the final products and dimensional parameters were measured by using the measuring tape. Pressure and pressing time was found directly from the secondary source. Duncun Multiple Range Test (DMRT) was used to evaluate the variability in the properties investigated.

Results

UF resin is used to manufacture both types of particle board. For achieving the greater efficiency of boards, some chemical compounds were added with the UF resin. In Jutex board with 100 lt UF resin 2.5 lt of 20% NH_4Cl solution was added in surface particle and 2.17 lt was mixed in core layer particles. However, Hexamine was used in a same proportion (217.39 g) in both surface and core particles bonding. Wax emulsion of 33% concentration (14.13 lt) was mixed for the adhesive of surface layer particles and for core particles 13.04 lt was added. But no fungicide was used in Jutex board manufacturing.

For the preparation of one batch adhesive for manufacturing woodex board 1.75 lt and 3.47 lt of 20% NH_4Cl solution were mixed in 100lt UF resin. In that mixture hexamine was also used for the adhesive for the surface particle bonding but for core layer this chemical was not added. Wax emulsion of 33% concentration was mixed as 12.5 lt in surface layer while in core layer it was used as 7.5 lt. During woodex board manufacturing, 625 g fungicide was used in both layers (Table 1).

Table 2 represents the physico-mechanical properties of boards having different thicknesses which were made up from jute sticks. The mass of a whole (8’ x 4’) board was varied significantly ($p \leq 0.05$) with 4 mm to 6 mm increase in thickness. But in case of 25 mm and 26 mm the masses were not varied significantly. The lowest mass was recorded for 12 mm board (22.27 kg) where the 41 mm board was the heaviest (53 kg). The particle densities in 12 mm (560.33 kg/m^3) and 18 mm board were found significantly higher than all others. No

Table 1 Chemical compositions of adhesives for jutex and woodex board manufacturing

Components	Jutex		Woodex	
	Surface layer	Core layer	Surface layer	Core layer
UF Resine (lt)	100	100	100	100
20% NH_4Cl solution (lt)	2.5	2.17	1.75	3.475
Hexamine (g)	217.39	217.39	375	0
33% Wax emultion (lt)	14.13	13.04	12.5	7.5
Fungicides (ml)	0	0	625	625

Table 2 Physico-mechanical properties of different boards made up of jute sticks

Type	Parameter Average									
	Mass (kg)	Density (kg/m^3)	BS (N/mm^2)	MOE (N/mm^2)	SS (N/mm^2)	TS (N/mm^2)	SW (N)	Pressure (bar)	PT (minute)	Temperature (^{o}C)
12 mm	22.27^f	560.33^a	10.96^a	1492.30^a	1.01^a	0.31^b	599.00^a	165.00^d	10.00^b	170.00^a
18 mm	32.00^e	528.33^b	9.28^a	893.00^b	0.93^a	0.45^a	626.33^a	173.33^c	7.00^c	170.00^a
25 mm	36.33^d	424.33^c	7.35^b	666.67^c	0.62^a	0.26^b	331.33^b	178.33^b	8.00^c	171.00^a
26 mm	37.50^d	424.67^c	7.07^{bc}	535.00^d	0.62^a	0.26^b	337.67^b	185.00^a	7.00^c	171.67^a
30 mm	42.33^c	393.67^d	5.39^{cd}	383.67^e	0.71^a	0.27^b	282.00^b	185.00^a	9.33^b	173.33^a
36 mm	46.67^b	385.67^d	5.46^{cd}	274.67^e	0.76^a	0.29^b	271.33^b	185.67^a	11.17^a	170.67^a
41 mm	53.00^a	365.67^d	3.97^d	299.67^e	0.83^a	0.28^b	172.67^c	183.00^a	11.83^a	172.67^a

Note: BS - bending strength, MOE - modulus of elasticity, SS - surface soundness, TS - tensile strength, SW - screw withdrawal, PT - pressing time, latter in suffix represents significant variation where $p \leq 0.05$

significant variation was observed between 25 mm and 26 mm board and among the 30 mm (393.67 kg/m^3), 36 mm (385.67 kg/m^3) & 41 mm (365.67 kg/m^3) particle boards. Bending strengths were measured significantly higher for 12 mm (10.96 N/mm^2) and 18 mm (9.28 N/mm^2) while the lowest bending strength was found for 41 mm (3.97 N/mm^2) which was statistically proved. The bending strengths were not varied notably for 25 mm (7.35 N/mm^2), 26 mm (7.07 N/mm^2) board and also for 30mm (5.39 N/mm^2), 36 mm (5.46 N/mm^2) jutex board. With the change of thickness, elasticities of boards were changed. The MOEs of 12 mm (1492.30 N/mm^2), 18 mm (893 N/mm^2), 25 mm (666.67 N/mm^2) and 26 mm (535 N/mm^2) were noticed to vary significantly from each other. But for 30 mm (383.67 N/mm^2), 36 mm (274.67 N/mm^2) and 41 mm (299.67 N/mm^2) the variation was not statistically significant. Surprisingly no significant variation of surface soundness was found among the tested boards. And only the tensile strength of 18 mm board (0.45 N/mm^2) was found significantly higher than all other board types while no such variation among the rest of the board types was observed. In case of screw withdrawal, the highest value was recorded for 18mm board (626.33 N) and the second highest screw holding capacity was measured for 12 mm (599 N) both of which were varied significantly in comparison to other types of board. On the otherhand, in 41 mm board (172.67 N) the screw withdrawal was found significantly lower than all other boards. But in 18 mm, 25 mm, 26 mm, 30 mm and 36 mm boards, the screw withdrawal values were not significantly varied with each other. The pressure applied to form a board were not significantly varied for 26 mm (185 bar), 30 mm (185 bar), 36 mm (185.67 bar) and 41 mm (183 bar) jutex board. Pressure required for 12 mm (165 bar), 18 mm (173 bar) and 25 mm (178 bar) which were significantly varied from each other. The variation of pressing time for 36 mm (11.17 min) and 41 mm (11.83 min) was significantly higher than other types of board. For the board having thickness 12 mm and 30 mm required to press for the similar period of time (10 min and 9.33 respectively) while pressing time for 18 mm (7 min), 25 mm (8 min) and 26 mm (7 min) were statistically proved as similar. But along with the pressing time the temperature were need not to change as there was no statistical variation was observed.

Table 3 depicts the physico-mechanical properties of boards having different thicknesses which were made up from wood particles of *Trewia nudiflora*. The mass of a full size board (8' x 4') board was varied significantly ($p \leq 0.05$) with 4 mm to 6 mm increase in thickness. The lowest mass was recorded for 12 mm board (29 kg) where the 25 mm board was the heaviest (49 kg). The particle densities in 12 mm (732.33 kg/m^3) and 18 mm (682 kg/m^3) board were found significantly different from each other. But the variation was observed between 16 mm and 18 mm board was not statistically supported. Bending strengths were measured significantly higher for 16 mm (10.96 N/mm^2) than the lowest bending strength of 25 mm (18.09 N/mm^2) board. The strengths were not varied notably for 12 mm (19.71 N/mm^2) and 18 mm (19.3 N/mm^2) board. With the change of thickness, elasticities of boards were changed. The MOE of 12 mm (2309.33 N/mm^2), 16 mm (2104 N/mm^2), 18 mm (1868.33 N/mm^2) and 25 mm (1428.33 N/mm^2) were noticed to vary significantly from each other. Surface soundness of 16 mm (1.82 N/mm^2) and 18 mm (1.85 N/mm^2) were not significantly different while surface smoothness of 12 mm board (0.66 N/mm^2) was significantly lower among the tested boards. And only the tensile strength of 12 mm board (0.43 N/mm^2) was found significantly higher than all other board types while no such variation among the rest of the board types was observed. In case of screw withdrawal, the lowest value was recorded for 25 mm board (859.67 N) which was varied significantly in comparison to other types of board. But in 12 mm, 16 mm and 18 mm boards, the screw withdrawal values were not significantly varied from each other. The pressures applied to form boards were exactly same as 280 bar. The variation of pressing time for 12 mm (3.40 min) was significantly lower than other types of board while pressing time for 16 mm (4.40 min), 18 mm (4.63 min) and 25 mm (4.40 min) were statistically proved as similar. But along with the pressing time the temperature in for the bottom platen was found significantly higher in case of only for 16 mm board (170 ^{o}C) but for other types of boards there was no statistical variation was observed.

Discussion

Board density, resin and wax and pressing condition are the major parameters that affect

Table 3 Physico-mechanical properties of different boards made up of wood particles

Type	Parameter Average									Temperature (^{o}C)	
	Mass (kg)	Density (kg/m^3)	BS (N/mm^2)	MOE (N/mm^2)	SS (N/mm^2)	TS (N/mm^2)	SW (N)	Pressure (bar)	PT (minute)	Top platen	Bottom platen
12 mm	29.00^d	732.33^a	19.71^{ab}	2309.33^a	0.66^c	0.43^b	1165.00^a	280	3.40^b	184.33	175^a
16 mm	36.00^c	714.00^{ab}	20.16^a	2104.00^b	1.82^a	0.66^a	1082.67^a	280	4.40^a	179.00	170^b
18 mm	40.17^b	707.33^{ab}	19.30^{ab}	1868.33^c	1.85^a	0.77^a	1068.67^a	280	4.63^a	185.00	175^a
25 mm	49.67^a	682.00^b	18.09^b	1428.33^d	1.00^b	0.65^a	859.67^b	280	4.40^a	185.00	176^a

Note: BS - bending strength, MOE - modulus of elasticity, SS - surface soundness, TS - tensile strength, SW - screw withdrawal, PT - pressing time, latter in suffix represents significant variation where $p \leq 0.05$

particleboard dimensional properties (Razali 1985). Similar result was also found in this study. UF resin was used to manufacture both types of particle board. UF adhesives are easy to work with, provide strong, durable bonds and are economical. Formaldehyde acts as the cross linker or polymerizer in UF adhesives (Nemlü 2002). For achieving the greater efficiency of boards, some chemical compounds were added with the UF resin. In Jutex board with 100 lt UF resin, 20% NH_4Cl solutions, Hexamine, Wax emulsion of 33% concentration were added. For the woodex boards, fungicide was added with the other chemical components as in jutex boards. But the mixing ratios were different between the board types and between the surface and core layer of the same type of boards.

The mass of a (8' x 4') woodex and jutex board was varied significantly ($p \leq 0.05$) with 4 mm to 6 mm increase in thickness. This proves that boards having 4 mm to 6 mm more thickness contain larger amount of particles. The particle densities in 12 mm (560.33 kg/m^3) and 18 mm board were found significantly higher than all others. The particle densities in 12 mm (732.33 kg/m^3) and 25 mm (682 kg/m^3) board were found significantly different from each other. No significant variation was observed between 16 mm and 18 mm board. Bending strengths were measured significantly higher for 12 mm (10.96 N/mm^2) and 18 mm (9.28 N/mm^2) while the lowest bending strength was found for 41 mm (3.97 N/mm^2). Bending strengths were significantly higher for 16 mm (10.96 N/mm^2) than the lowest bending strength of 25 mm (18.09 N/mm^2). The bending strengths were not varied notably for 12 mm (19.71 N/mm^2) and 18 mm (19.3 N/mm^2) board. For both types of boards the highest thickness contain the lowest bending strength. The boards having the high thickness include more core particles which are larger in size. Presence of larger size particles reduces the strength of bonding among the particles. Moreover, wood properties influence the composite performance especially MOE and tensile strength (Maloney 1977, Haygreen & Bowyer 1996). With the change of thickness, elasticities of both types of boards were changed. But in jutex board after reaching the thickness of 30 mm the boards were not different in terms of MOEs. Surprisingly in jutex boards, no significant variation of surface soundness was found among the tested boards. On the otherhand, surface soundness of woodex boards in 16 mm (1.82 N/mm^2) and 18 mm (1.85 N/mm^2) were not significantly different while surface soundness of 12 mm board (0.66 N/mm^2) was significantly lower among the tested boards. This represents jutex boards ensure smoother surface than woodex boards. And only the tensile strength of 18 mm board (0.45 N/mm^2) was found significantly higher than all other board types while no such variation among the rest of the board types was observed. But in woodex boards the highest tensile strength was achieved in 12 mm board (0.43 N/mm^2). In case of screw withdrawal, the highest value was recorded for 18 mm jutex board (626.33 N). On the otherhand, in 41 mm jutex board (172.67 N) the screw withdrawal was found significantly lower than all other boards. But in 18 mm, 25 mm, 26 mm, 30 mm and 36 mm boards, the screw withdrawal values were similar. The lowest value was recorded for 25 mm woodex board (859.67 N) which was varied significantly in comparison to other types of board. But in 12 mm, 16 mm and 18 mm woodex boards, the screw withdrawal values were not significantly varied from each other. The pressures applied to form a board were similar for 26 mm (185 bar), 30 mm (185 bar), 36 mm (185.67 bar) and 41 mm (183 bar) jutex board. But from 12 mm to 25 mm thickness the pressure requirement was significantly different. In case of woodex boards the pressures applied for board formation were exactly same as 280 bar. The variation of pressure in jutex board represents that those were more susceptible to burst than woodex board. The variation of pressing time for 36 mm (11.17 min) and

41 mm (11.83 min.) jutex boards were significantly higher than other types of board. The variation of pressing time for 18 mm (4.63 min) and 25 mm (4.40 min) were statistically proved as similar higher than other woodex boards. This is may be caused that the boards having higher thickness include more adhesive and obviously require more time to cure. To produce satisfactory contact between particles, it is usually necessary to compress the board to 1.2-1.6 times that of the required specific gravity (Suchsland and Xu 1989). Along with the pressing time the temperature were need not to change as there was no statistical variation was observed. In case of woodex boards, in the bottom platen the temperature was found significantly higher in case of only for 16 mm board (170^{o}C).

Conclusions

Jute sticks are usually used as fuelwood in the rural areas of Bangladesh. At the same time *Trewia nudiflora* virtually does not have the timber value. But the boards which were made from these two added a great value to their uses. In Bangladesh, Jutex boards are largely used for making flush doors, veneered boards and woodex boards are used to make laminated boards. All these products possess high demand in the local market. Since, none of those raw materials were coming from the natural forest, those paneled products releasing the pressure on the forest reserve.

References

ABTP (Advance Buildings Technology and Practices), 2005. Finishes and Furnishings: strawparticleboard. www.advancebuildings.org/_frames/fr_t_straw_particleboard.htm.

Alma M.H., Kalaycroglu H., Bektas I. & Tutus A., 2004. Properties of cotton carpel based particleboards, Industrial Crops and Products, 22: 141-149.

Anonymous, 2000. Definition of particle board, In. American Heritage Dictionary of the English Language, Fourth Edition, Houghton Miffilin Company.

ANU Forest Market Report, 2002. http://sresassociated.anu.edu.au/marketreport/report 20. pdf.

Basturk M.A., 1993. Investigation of particleboard manufacture from *Thuja plicata*. Istanbul University. J. Forestry, 43: 155-168.

Cai Z., Wu Q., Lee J. & Hiziroglu S., 2004. Influence of board density, mat construction and chip type on performance of particleboard made from eastern redcedar. Forest Products J., 54: 226- 232.

Charles C., 1986. Wood particle and flakeboard: Types, grades, and uses. In General Technology Report FPL-GTR-53, Madison, WI: US Department of Agriculture., Forest Service. Forest Products Laboratory.

Cook D.F., Ragsdale, C.T., Major R.L., 2000. Combining a neural network with a genetic algorithm for process parameter optimization. Eng Appl Artif Intell 13, 391-396.

Drake P.A., 1997. The composite panel industry: A Global market assessment. 31st International Particleboard/Composite Materials Symposium, Washington State University, Pullman, USA.

Haygreen J.G., Bowyer J.L., 1996. Forest Products and Wood Science: An Introduction. Third edition. The Iowa State University Press, Iowa.

Izran K., Zaidon A., Rashid A.M.A., Abood F., Zaihan J., Beyer G., 2009. Fire Resistance and early burning performance of kenaf (*Hibiscus cannabinus*) particleboard treated with phosphorous based fire retardants, in Proceedings of National Postgraduate Conference on Engineering, Science and Technology, Universiti Teknologi Petronas: Malaysia, pp. 83.

Kittisiri A., 1996. Impact of monoculture: The case of eucalyptus plantation in Thailand. Environmental and Social Effects and Sustainability Alternative Conference. Songkhla, Thailand.

Kozlowski R., Helwig M., 1998. Lignocellulosic polymer composite', In: Prasad, P.N. (ed), Science and Technology of Polymer and Advanced Materials, Plenum Press, New York.

Maloney T.M., 1977. Modern Particle Board and Dry Process Fibreboard Manufacturing. Miller Freeman Publications, San Francisco.Suchsland O & Xu H. 1989. A simulation of horizontal density distribution in a flakeboard. Forest Products Journal 9: 52-60.

Nemlü G., 2002. Factors Affecting the Production of E1 Type Particleboard. Turk J Agric For, 26: 31p.

Park S.J., Lee J.J., 2004. Fire resistance of light-framed wood floors exposed to real and standard fire, Journal of Fire Sciences, 22: 449-471.

Rashid A.M.A., Chew L.T., 1990. Fire retardant treated chipboards, In. Conference on Forestry and Forest Product Resource. CFFPR-90, Malaysia, pp.37.

Sellers T., 2000. Growing Markets for Engineered Products Spurs Research. Wood Tech. 127(3): 40-43.

Stark N.M., Cai Z., Carll C. undated. Wood-Based Composite Materials. General Technical Report FPL–GTR–190, Chapter-11, 11p.

Strategis, 2005. Wood-based Panel Products Technology Roadmaps: V. Particleboard.http//www.strategis.ic.gc.ca/epic/internet/infi-if.nsf/en/fb01136e. html. accessed in January, 2005.

Sutton W.R.J., 1993. The World's Need For Wood, In Proceedings of The Globalisation Of Wood Conference - Supply Processes Products and Markets, Forest Products Society 1 Nov, 1993, Portland Oregon.

Youngquist J.A., 1999. Wood-based composites and panel products. In: Wood Handbook: Wood as an Engineering Material. Gen. Tech. Report. FPL-GRT-113. USDA Forest Serv., Forest Prod. Lab., Madison, WI, pp. 1-31.

Zheng Y., Pan R., Jenkins B.M., Blunk S., 2006. Properties of medium-density particleboard from saline Athel wood, Industrial Crops and Products, 23: 318-326.