EFFECT OF CEMENT/WOOD RATIO ON THE RELATIONSHIP BETWEEN CEMENT BONDED PARTICLEBOARD DENSITY AND BENDING PROPERTIES

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OYAGADE, A. O. 1990. Effect of cement/wood ratio on the relationship between cement bonded particleboard density and bending properties. This study was undertaken to investigate the relationship between density and bending properties of cement bonded particle board as influenced by cement/wood ratio. The experimental boards were made at three cement/wood ratios: 1.55/1, 2.33/1 and 3.10/1 (weight to weight basis). The observed density range at each of these cement/wood ratios was 620 to 870, 830 to 1230 and 870 to 1230 $kg\ m^{3}$, respectively. The bending properties of the board including Modulus of Elasticity (MOE), Modulus of Rupture (MOR) and Work Done in bending (WD) all increased linearly with increase in density. The effect of changing cement/wood ratio was less important on MOE than on MOR and Work Done in bending. A constant board density increase in cement/wood ratio resulted in a decrease in the bending properties of the board.

Key words: Cement particleboard - density - MOE - MOR - Work Done

Introduction

Particleboard manufactured using mineral cement as the binding agent is gradually gaining importance in many countries of the world. The emergence of interest in this board, particularly among the developing nations, can be associated with the local availability of cement in many of these countries and the possibility to adapt the board manufacturing process to a low level of technology. The board superiority to resin bonded particleboard with respect to combustibility, durability, weatherability and dimensional stability makes it a useful constructional material in areas where fire and moisture preclude the use of resin bonded particleboard. In addition, the problem of formaldehyde release often associated with urea-formaldehyde bonded board, which has received a great deal of attention from various regulatory bodies of the world does not occur with cement bonded particleboard. It is a board with considerable potential as a sheet construction element for commercial and industrial buildings as well as for low cost houses.

At present, commercially manufactured cement particleboards are commonly found to be produced within a density range of 1100 to 1300 *kg m*^{3}. The characteristically high density of the board is a possible limitation to the use of the board, particularly in areas where weight saving is esssential. For instance, it is desirable that density be reduced to allow easier site handling and application in situations such as ceiling panels. As noted by Deppe (1974), there is the need for research efforts directed at finding ways of reducing the density of the board whilst simultaneously improving its strength properties. It is considered that the problem of high density of the board can first be tackled through manipulations of the board process variables which are capable of influencing density and the relationship that may exist between density and strength properties of the board over a range of combinations which is practically feasible.

An important manufacturing process variable which tends to predominate in influencing the final density of the board is cement/wood ratio. In a study by Moslemi *et al.* (1987), the influence of cement/wood ratio on the Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) of the board was examined. In this study, there was no attempt made to relate density of the board at varying cement/wood ratio to the static bending properties of the board. Obviously, by varying cement/wood ratio, the density as well as the strength properties of the board can be varied. The objective of this study was to evaluate the bending properties of the board over a density range extending below the density range of commercially produced board, and to examine how the relationships between density and the bending properties are influenced by changing cement/wood ratio.

Materials and method

The manufacturing process variables of cement particleboard under investigation in this study were cement/wood ratio at levels: 1.55/1, 2.33/1 and 3.10/1 weight of cement to wood, and board density at the following nominal densities: 600, 750, 900, 1050 and 1200 *kg m*^{3}. The term "nominal density" as used here is the sum of the oven dry weight of wood particles and dry cement needed for fabricating a board divided by the intended volume of board. The two study variables were combined as indicated in Table 1. It is practically impossible to produce sufficiently consolidated boards at nominal density of 600 *kg m*^{3} using cement wood ratios 2.33/1 and 3.10/1. Also, in order to produce boards at density levels of 1050 and 1200 *kg m*^{3} using cement wood ratio of 1.55/1, excessive pressure which may lead to crushing of some of the wood fibres will be required. Hence, boards were not prepared at these combinations.

Table 1. Experimental design

Cement/wood ratio	Nominal board density ($kg\ m^3$)				
	600	750	900	1050	1200
1.55/1	X	X	X	-	-
2.33/1	-	X	X	X	X
3.10/1	-	X	X	X	X

(Note: X stands for combinations at which production of experimental boards were practically feasible; at other combinations (marked ' - ') production of good quality boards were not feasible).

The amount of water for blending was held at a constant of 65% mass of cement. Theoretically, dry cement requires an amount of water equivalent to 23% of its own weight for hydration process. In order to obtain a uniform coating of the cement on the wood particles, and for the hydration process to proceed to completion, an amount of water in excess of that theoretically required for hydration process is essential. In a previous study (Oyagade 1988), an amount of water equivalent to 65% the mass of cement was found to be the most adequate for promoting uniform blending and efficient inter-particle bonding when cement/wood ratios in the range of 1.55:1 to 3.10:1 are employed.

The experimental boards were made using Norway spruce (*Picea abies*). The choice of this wood species was based on the fact that it has little or no inhibitory effect on cement setting. The Norway spruce logs were cross cut into bolts (suitable for the flaking machine used), debarked and soaked for two weeks in water at 60° *C* to facilitate production on high quality flakes. Following flaking, using a laboratory disc flaker, the flakes were immediately dried in a kiln to about 12% moisture content and stored in sealed polythene bags. The flakes obtained were approximately 0.4 *mm* thick, 3.8 *mm* wide and 20 *mm* long. The cement binder used was Ordinary Portland cement manufactured in the United Kingdom under the trade name "Blue Circle". The cement was a general purpose type. It had physical characteristics and chemical composition complying with BS 12: Part 2: 1971 "Specification for Portland Cement (Ordinary and Rapid-hardening)".

For board fabrication, the quantity of wood flakes, water and cement required to form boards measuring 250 *mm* wide, 300 *mm* long and 15 *mm* thick was weighed out. The weight of water needed was calculated to include the initial weight of water in the flakes. The ingredients were mixed in the following order to keep conditions as nearly uniform as possible. First, the correct amount of wood flakes was placed in a large mixing bucket. About half of the water required for the board preparation was added very slowly to the wood flakes while stirring to give an even distribution of moisture on the surfaces of the flakes. The appropriate weighed amount of cement was added, and thorough hand mixing was continued until the cement coating on the surfaces of the flakes appeared to be homogeneous. The remaining water was then added and the ingredients were then further hand mixed for 10 *min*.

The mix was immediately felted by hand as evenly as possible onto 250 × 300 *mm* caul plate that has been over-laid with polythene sheet. This sheet prevents sticking of the board onto the plate. After felting, another polythene sheet was placed on the mattress before the top caul plate was positioned on it. The felted mattress was transferred to the press and pressed to stops at 15 *mm* thickness. While still in the press, the top caul plate was bolted down on the mattress so that upon removal from the press the mattress was still under pressure. The mattress, sealed in polythene bag, was left under pressure for 48 *h* in a room controlled at a relative humidity of 65% and 20°*C*. Thereafter the pressure was released and the boards were stripped off the caul plates. After curing them further for five days in sealed polythene bags, the boards were trimmed and cut to required test specimen sizes. The test pieces were conditioned in a room maintained at 20°*C* and 65% relative humidity to attain constant weight. Bending test on the boards was carried out in accordance with BS5669: 1979, 29 days after preparation of the individual boards.

Each variable combination in this study was replicated two times giving a total of 22 boards produced. Four static bending test specimens were obtained from each board. This gave a total of eight test specimens per variable combination.

Results and discussion

The bending properties [Modulus of Elasticity (MOE), Modulus of Rupture (MOR), and Work Done in bending (WD)] observed for boards prepared using 11 different variable combinations are presented in Table 2. As evident from this table, the observed average board density for most of the boards varied from the planned (nominal) density. The observed variations can probably be associated with error in manual felting, increase in board thickness resulting from reversal of compressive stresses imposed on the board during pressing following release of the pressure, shrinkage of cement paste following drying or reduction in the specific gravity of the cement paste component following hydration - the specific gravities of 3.15 and 2.65 are reported for anhydrous and hydrated cement respectively (Powers 1964, Murduck *et al.* 1968). The variations may also be explained by weight increase of the binder following hydration. As mentioned earlier, water amounting to about 23% mass of dry cement chemically combines with the dry cement during hydration process. These variations in density not withstanding, regression analysis can still be used as a statistical tool for establishing possible relationship between density and the bending properties of the board.

Table 2. Bending properties of cement bonded particleboard made at three cement/wood ratios

Board number	Cement/ wood ratio	Density ($kg\ m^{-3}$)		MOE (MPa)	MOR (MPa)	Work Done ($\times 10^{-3}$ $mm\text{-}N\ mm^{-3}$)
		Nominal	Observed			
1	1.55/1	600	620	980	5.64	6.64
2	1.55/1	750	790	2050	12.62	11.32
3	1.55/1	900	870	2210	15.12	16.42
4	2.33/1	750	830	2190	11.25	10.15
5	2.33/1	900	960	3010	16.52	16.06
6	2.33/1	1050	1020	3130	17.24	15.06
7	2.33/1	1250	1230	3590	23.84	20.04
8	3.10/1	750	870	2300	9.05	6.94
9	3.10/1	900	950	2610	10.96	9.26
10	3.10/1	1050	1050	2980	15.74	11.90
11	3.10/1	1200	1230	3400	22.15	17.56

(Each value is an average of eight specimens)

The relationships between the observed density and static bending properties of the board are illustrated in Figures 1 to 3. These illustrations contain regression lines fitted using equations (Table 3) derived from simple linear regression analysis of the bending properties on board density at each level of cement/wood ratio and for the pooled data points. The figures (1 to 3) show that at each level of cement/wood ratio, the three bending properties were improved with increase in board density. This observation is not surprising. At a constant level of other factors, including cement/wood ratio, increase in board density achieved essentially by increasing the amount of wood particle-cement paste mix compressed to a given board dimension should be expected to result in boards having better interparticle contact, improved bonding between particles, higher densification of individual particles, and more material to distribute stresses within the board. Improvement in strength properties with increase in density has also been reported for resin bonded particleboard (Lynam 1959, Gatchell *et al.* 1966, Vital *et al.* 1974, Kelly 1977, Chew *et al.* 1988).

When all the boards are examined together, some of the boards at the low level of cement/wood ratio exhibited better bending properties compared to boards of the same density at high cement/wood ratio (Figures 1 - 3). This could be that a given weight of the wood particle-cement paste mix of a low cement/wood ratio occupies a greater volume than the same weight of a mix of high cement/wood ratio. When such mixes are compressed to the same dimension of a board, the mix of low cement/wood ratio will give a higher relative interparticle contact resulting in a better bond between the wood particles, and consequently in the formation of a stronger board. The figures show MOE for the pooled data points to be more closely related to density than it is to MOR and Work Done in bending. This suggests that MOE can be predicted more accurately than MOR and Work Done in bending using density alone as a function of the bending properties. With MOR and Work Done in bending, as shown in Figures 2 and 3, the effect of changing cement/wood ratio appears to be very important. The two figures show that at density levels from about 800 $kg\ m^3$ and above, improvements in MOR and Work Done in bending were enhanced by decreasing cement/wood ratio from 3.10/1 to 2.33/1. However, the significance of the effect caused by the variation in cement/wood ratio becomes reduced as density is increased. Similarly, a reduction in cement/wood ratio from 2.33/1 to 1.55/1 brought about improvement in both MOR and Work Done in bending. At this range of cement/wood ratio, and within the range of density from about 700 to 870 $kg\ m^3$, the significance of the effect of varying the cement/wood ratio is increased with increase in density. Moslemi *et al.* (1987) also observed bending strength (MOR) to be significantly enhanced by decreasing the cement/wood ratio from 3.0/1 to 2.0/1. Modulus of Elasticity also increased with increase in cement/wood ratio, but it was influenced to a lesser extent compared to MOR and Work Done in bending when cement/wood ratio was varied from 2.33/1 to 3.10/1.

Table 3. Regression equations relating bending properties and density of cement bonded particleboard made at three cement/wood ratios

Cement/wood ratio	Variable Y = a + b (density)	R^2	Y-Value when D = 1000 $kg\ m^3$
1.55/1	MOE = -2187.19 + 5.1793D	0.96	-
2.33/1	MOE = -450.91 + 2.2881D	0.90	2837 *MPa*
3.10/1	MOE = -598.69 + 3.3232D	0.99	2725 *MPa*
Pooled	MOE = -1172.32 + 3.9593D	0.93	2787 *MPa*
1.55/1	MOR = -18.27 + 0.0387D	0.99	-
2.33/1	MOR = -13.55 + 0.0304D	0.99	16.85 *MPa*
3.10/1	MOR = -23.97 + 0.0376D	0.99	13.63 *MPa*
Pooled	MOR = -11.29 + 0.0273D	0.84	16.01 *MPa*
1.55/1	WD = -16.65 + 0.0374D	0.94	-
2.33/1	WD = -7.95 + 0.0229D	0.90	14.95×10^{-3} *mm-N mm*^{3}
3.10/1	WD = -19.26 + 0.0295D	0.99	10.24×10^{-3} *mm-N mm*^{3}
Pooled	WD = -5.15 + 0.0188D	0.59	13.65×10^{-3} *mm-N mm*^{3}

(MOE - Modulus of Elasticity; MOR - Modulus of Rupture; WD - Work Done; D - Density)

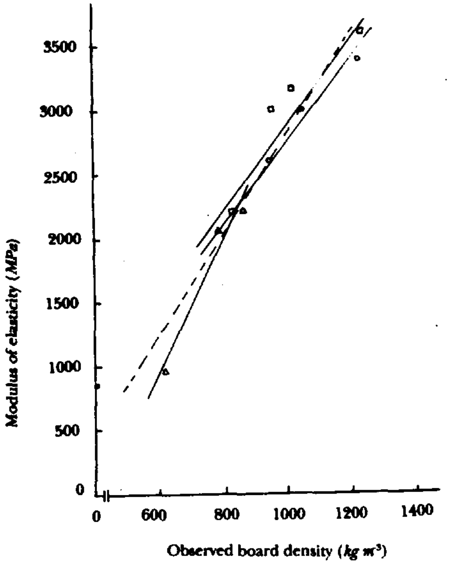

Figure 1. Relationship between board density and Modulus of Elasticity of cement bonded particle board made at three cement/wood ratios

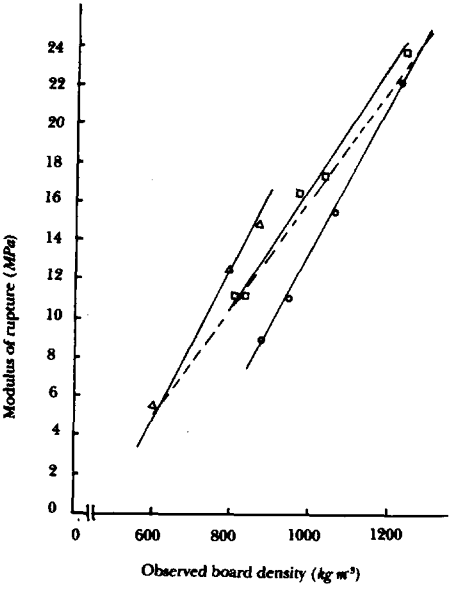

Figure 2. Relationship between board density and Modulus of Rupture of cement bonded particleboard made at three cement/wood ratios

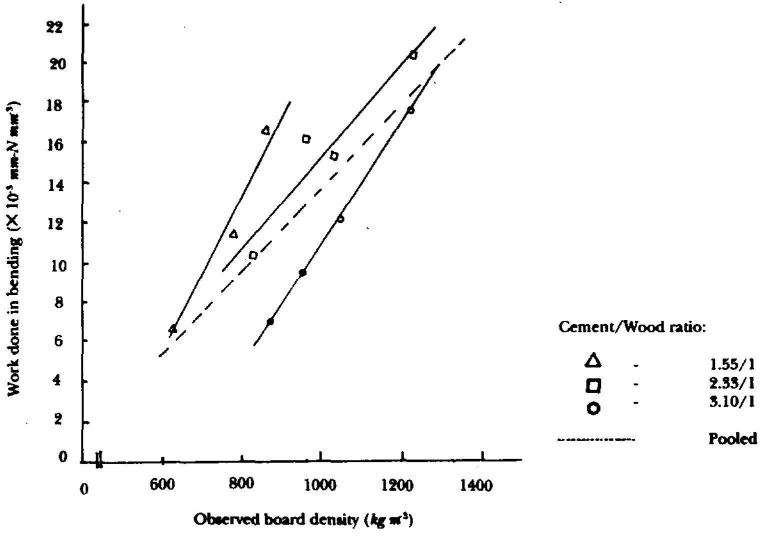

Figure 3. Relationship between board density and Work Done in bending of cement bonded particleboard at three cement/wood ratios

The results of linear regression analysis of the bending properties on board density are given in Table 3. The values of coefficient of determination (R^2) obtained for the pooled data were 93, 84 and 59%, for MOE, MOR and Work Done in bending, respectively. This indicates the importance of cement/wood ratio in determining these properties. Predictions of bending properties at a density level of 1000 *kg m*$^{-3}$ and at each level of cement/wood ratio, using the regression equations are given in Table 3. The regression relationships established here between board density and the bending properties are purely empirical. Thus, in order to make valid predictions based on the regression relationships, the predictions need to be made within the limits of board density and cement/wood ratio examined. The range of density observed for the set of boards made at cement/wood ratio of 1.55/1 was 620 to 870 *kg m*$^{-3}$. Therefore, prediction at a density level of 1000 *kg m*$^{-3}$, using the relationship established for this set of boards cannot be valid. It is for this reason that no predictions were made at cement/wood ratio of 1.55/1.

Again, it becomes evident from the predicted values that increase in MOE, MOR and Work Done in bending occurred with reduction in cement/wood ratio. At a density of 1000 *kg m*$^{-3}$, and at cement/wood ratio of 3.10/1, the equation gave 2725 *MPa* for MOE, 13.63 *MPa* for MOR and 10.24×10^{-3} *mm-N mm*$^{-3}$ for Work Done in bending, whereas at this same density, and at cement wood ratio of 2.33/1, the values obtained are 2837 *MPa*, 16.85 *MPa* and 14.95 $\times 10^{-3}$ *mm-N mm*$^{-3}$, for MOE, MOR and Work Done in bending, respectively. The observation made here also agrees with that by Lee (1985) in a study on cement-bonded excelsior board. He reported increase of cement/wood ratios above 2.0/1 to have an adverse effect on bending stiffness (MOE) and strength (MOR) of the board.

Conclusion

Within the range of cement/wood ratio employed and board density observed in this study, it was found that board density was linearly and positively related to the bending properties of cement bonded particleboard when cement/wood ratio was held constant. However, when boards prepared at varying cement/wood ratio were compared, the effect of cement/wood ratio was very important in determining the bending strength (Modulus of Rupture and Work Done in bending). At constant board density level, decrease in cement/wood ratio generally improved the bending properties. The effect of changing cement/wood ratio was stronger on MOR and Work Done in bending than on MOE.

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