DEFORMATION OF WOOD IN COMPRESSION DURING MOISTURE MOVEMENT

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ABSTRACT

This work presents the phenomenon of mechano-sorptive strain in the deformation of wood during moisture content (MC) changes. A series of experiments were designed to demonstrate the greatly enhanced deformation due to the mechano-sorptive effect. The purpose of this work is to show the magnitude of mechano-sorptive creep compared to the ordinary viscoelastic creep with applied compressive load. In order to do this, several conditions were induced. They were the moisture movement with MC change, moisture movement without MC change and conditions without moisture movement. Several apparatus were assembled to produce the desired conditions. Special care is taken to make sure that the compressive load is relatively small and is within elastic limit. This work observed the unique patterns of strains of various conditions that were induced in the experiments. The characteristics shown in the results were evaluated logically and compared to existing theories to confirm their validity. The results have shown that with the presence of mechano-sorptive, the maximum strains of Jelutong (*dyera costulata)* wood specimens loaded at 200N is 0.433×10^{-3}. The results showed that the severest deformation is caused by the increasing MC in the wood specimen, attributed to the mechano-sorptive (MS) effect.

Keywords: *moisture content, mechano-sorptive and viscoelastic*

1. INTRODUCTION

Wood can be best understood as a fiber-reinforced composite material [1]. Composite interactions can occur on several levels of physical structure. At the cell wall layer, composite action takes place between oriented, fibrous, framework material and amorphous matrix material. Dry wood is primarily composed of cellulose, lignin, hemicelluloses, and minor amounts of extraneous materials (5 - 10%). Cellulose is the major component, constituting approximately 50% of wood substance by weight. During growth of the tree, the cellulose molecules are arranged into strands called fibrils. Fibrils are then organized to make up the cell wall of wood fibers. Most of the cell wall cellulose is crystalline.

Lignin constitutes 23 - 33% of the wood substance in softwoods and 16 - 25% in hardwoods. It is concentrated toward the outside of the cells and between cells. Lignin binds individual cells together. Hemicelluloses play an important role in fiber-to-fiber bonding. Lignin and hemicelluloses combine to form the matrix in which the cellulose microfibrils are embedded [2]. Their structure inside the wood cell wall is thought to be that of a water-swelling gel [3]. They are soluble in alkali and water. Extractives include tannins and other polyphenolics, coloring

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matter, essential oils, fats, resins, waxes, gum starch and simple metabolic intermediates [4]. This component is termed extractives because it can be removed from wood by extraction with solvents, such as water, alcohol, acetone, benzene, or ether. Extractives may constitute roughly 5 - 30% of the wood substance, depending on factors such as species, growth conditions and time of year when the tree is cut.

MC of wood is defined as the weight of water in wood expressed as a fraction, usually a percentage, of the weight of oven dry wood [5]. Weight, shrinkage, strength, and other properties depend upon the MC of wood [6]. MC can range from about 30 - 200% of the weight of wood substance. In softwoods, the MC of sapwood is usually greater than that of heartwood. In hardwoods, the difference in MC between heartwood and sapwood depends on the species. Variability of MC exists even within individual boards cut from the same tree. The equilibrium MC (EMC) of timber is that moisture at which timber neither loses nor gains moisture from the surrounding atmosphere [7].

The MC at which only the cell walls are completely saturated but no water exists in cell lumens is called the fiber saturation point (FSP) [8]. In practical however, it is possible for all cell lumens to be empty and have partially dried cell walls in one part of a piece of wood, while in another part of the same piece, cell walls may be saturated and lumens partially or completely filled with water. It is even probable that a cell wall begin to dry before all the water has left the lumen of that same cell. [6]. The FSP of wood averages about 30%MC, but in individual species and individual pieces of wood it can vary by several percentages [9]. The FSP is considered as that MC below which the physical and mechanical properties of wood begin to change as a function of MC. During drying, the outer parts of a board can be less than fiber saturation while the inner parts are still greater than fiber saturation [10].

2.   MATERIALS AND METHODS

Jelutong *(Dyera Costulata.)* wood species are used throughout the entire experiments. The wood is white or straw colored and there is no differentiation between heartwood and sapwood [4]. The texture is moderately fine and even. The grain is straight and the luster is low. The wood weighs about 465 kg/m^3 at 12% MC. The wood is very easy to dry with little tendency to split or warp. The test specimen was 100 mm long and 640 mm^2 in cross section with the grain parallel to the length. A 14mm diameter hole was drilled longitudinally through the specimen to form a hollow core to enable a moisture gradient to be maintained through the specimen without causing a change in MC. The ends of the specimen were smeared with wax and metal plates were placed over the ends to seal off the core.
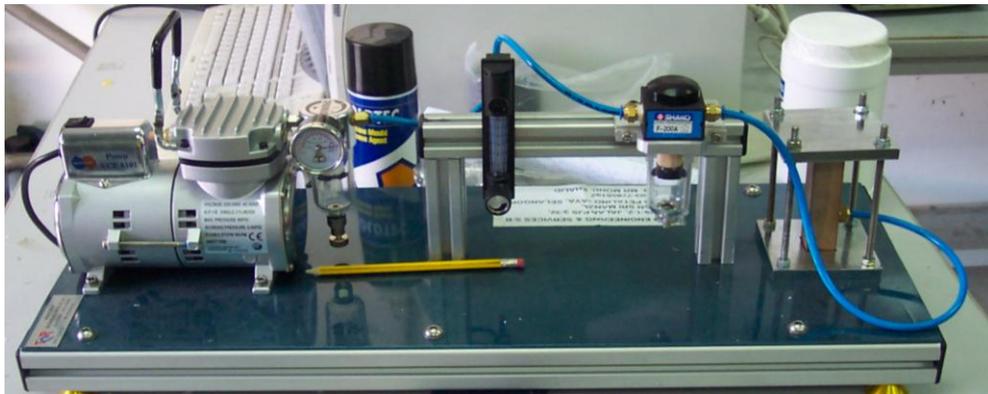

Fig. 1: Vacuum pump assembly.

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To evaluate the deformation due to the MS effect, the strain ε_m due to the moisture movement and MC change within wood is defined as $\varepsilon_m = \varepsilon_{vc} + \varepsilon_{ms} + \varepsilon_s$ where ε_m is the total measured strain, ε_{vc} is the normal viscoelastic creep (constant MC), ε_{ms} is the MS strain under changing MC and ε_s is the swelling or shrinkage strain of an unloaded specimen. The component of interest is the MS strain, ε_{ms} which is calculated as $\varepsilon_{ms} = \varepsilon_m - \varepsilon_{vc} - \varepsilon_s$. Thus, several conditions are simulated to yield these strains.

Figure 1 shows the vacuum pump that is used during the experiment to induce moisture movement in wood specimens. The assembly includes several valves to regulate pressure. The vacuum has a specification of 1/8 hp, capacity of 16 liters/minute and a working pressure of up to 60Psi. A Mitutoyo dial indicator (a resolution of 0.01 mm on the major scale and 0.001mm on the minor scale) is used to measure height changes during the swelling and shrinkage experiments. Measurements are taken on several time intervals and the deviation from zero point is observed to be the deflection.

3. WOOD SPECIMEN CONDITIONING

The specimens are prepared with three conditions namely dry, water-saturated and in equilibrium to ambient air of 65% relative humidity (RH). The dry condition is produced using an oven with blowing air at 105ºC. The wood specimens are weighted initially and at several time intervals. The wood is assumed to be dry when there is no more change in weight. The percentage of MC is calculated using the following formula:

$$MC\,(\%) = \frac{\text{Weight when cut - Ovendry weight}}{\text{Ovendry weight}} \times 100$$

The water-saturated condition is produced using vacuum chamber with partially filled water. To produce EMC with air humidity of 65%RH, the wood specimen is sealed at both ends. A tube is attached to a hole at the side of the specimen and connected to a vacuum pump to pump in the ambient air. The condition is assumed in equilibrium when there is no more change in weight.

4. EXPERIMENTAL CONDITIONS

There are seven experimental conditions:

(i) The increasing MC (IMC) condition is induced by applying a constant compressive load of 200N on oven-dried wood specimen. The wood specimen is sealed at both ends. Ambient air of 65%RH is pumped into and through the wood specimen. The dry wood retains some of the moisture from the ambient air and thus increases MC.

(ii) The decreasing MC (DMC) condition is induced by applying a constant compressive load of 200N on water-saturated wood specimen. Moisture is pumped out of the wood as ambient air passes through the wood. Air of 65%RH replaces water in the wood pores, resulting in decreasing MC.

(iii) The wet uniform MC (wet MC) condition is induced by applying a constant compressive load of 200N on water-saturated wood specimen that is submerged in water container without the vacuum pump. This results in no change in MC.

(iv) The dry uniform MC (dry MC) condition is induced by applying a constant compressive load of 200N on oven-dried wood specimen that is wrapped in an aluminium foil to impede moisture from entering the wood without the vacuum pump. This will also results in no change in MC.

(v) The moisture movement (MM) condition is induced by applying a constant compressive load of 200N on wood specimen that is in equilibrium with room condition. With the vacuum pump ambient air passes through the wood pores and moisture from ambient air replaces those within the wood, resulting in MM without change in MC.

(vi) The swelling condition is induced using the vacuum pump without applying any compressive load on oven-dried wood specimen which is sealed at both ends. Moisture from ambient air will enter the wood, causing it to swell. The deflection of the wood specimen is measured using a dial indicator at several time intervals.

(vii) The shrinkage condition is induced using the vacuum pump without any compressive load on water-saturated wood specimen. Moisture from within the wood is pump out, causing it to shrink.

The *corrected* DMC condition is where the effect of shrinkage has been subtracted from the initial DMC condition. The *corrected* IMC condition is where the effect of swelling has been subtracted from the initial IMC condition.

5. RESULT AND DISCUSSIONS

Table 1 presents a summary of all the data after rearrangements and mathematical computations. The data are used to generate graphs of all the conditions. It can be observed from the table that the strain for corrected DMC i.e. after correction due to shrinkage becomes steady at 0.029 mm whereas for corrected IMC, it becomes steady at 0.033 mm. These values seem small in most engineering applications since the specimens are only 100mm long and loaded at only 200 N, which are hardly the common parameters where wood is utilized. Most common engineering structures involve much greater loads and longer wood members that are sufficient to warrant significant deformations.

Table1: *Strain at 15 minutes interval for DMC, IMC, wet MC, dry MC, MM , Swell, Shrink, CDMC and CIMC.*

| Temp ^oC	DMC	IMC	MC	Dry	MM	swell	shrink	CDMC	CIMC
0	0	0	0	0	0	0	0	0	0
15	0.1505	-0.08	0.2214	0.0639	0.0925	-0.27	0.0295	0.1210	0.1899
30	0.2303	-0.12	0.2687	0.0688	0.1082	-0.38	0.0393	0.1909	0.2618
45	0.2706	-0.14	0.2883	0.0718	0.1181	-0.42	0.0492	0.2214	0.2844
60	0.3070	-0.15	0.2952	0.0728	0.1279	-0.46	0.0590	0.2480	0.3051
75	0.3307	-0.16	0.3021	0.0738	0.1348	-0.48	0.0639	0.2667	0.3198
90	0.3464	-0.17	0.302	0.075	0.1377	-0.51	0.073	0.2726	0.337
105	0.3543	-0.18	0.309	0.078	0.1377	-0.52	0.078	0.2755	0.337
120	0.364	-0.19	0.302	0.078	0.1377	-0.53	0.088	0.2755	0.335
135	0.368	-0.20	0.30905	0.0787	0.14173	-0.54	0.0984	0.26968	0.33070
150	0.3759	-0.22	0.2982	0.078	0.1446	-0.55	0.1033	0.2726	0.3248
165	0.3877	-0.22	0.3120	0.078	0.1417	-0.56	0.1131	0.2746	0.3375
180	0.4025	-0.24	0.3188	0.078	0.1417	-0.57	0.1181	0.2844	0.3238
195	0.4064	-0.25	0.3120	0.078	0.1446	-0.59	0.1279	0.2785	0.3346
210	0.4133	-0.26	0.3120	0.077	0.1417	-0.61	0.1377	0.2755	0.3425
225	0.4251	-0.28	0.3188	0.078	0.1446	-0.62	0.1427	0.2824	0.3346
240	0.4330	-0.29	0.3120	0.078	0.1476	-0.63	0.1476	0.2854	0.3425
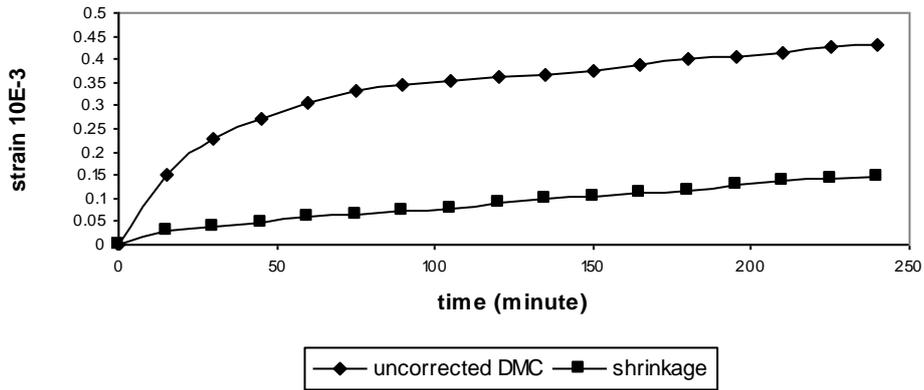
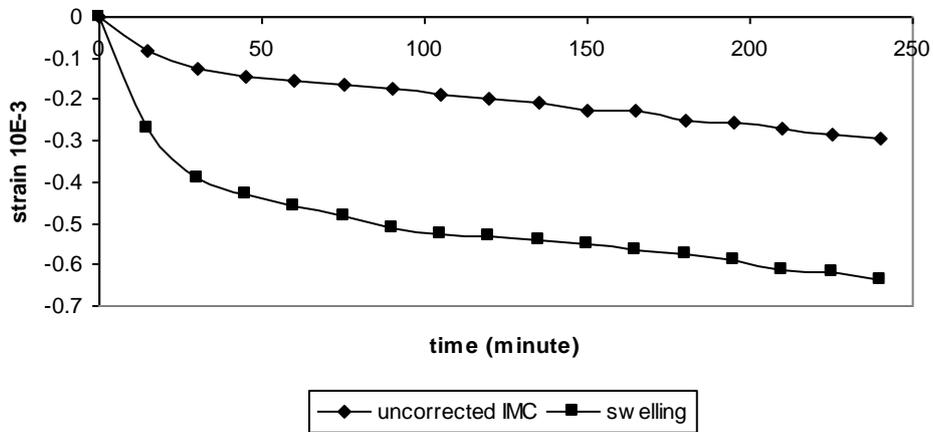***Fig. 2:*** *Strain vs time for DMC (uncorrected) and shrinkage.*

Fig. 3: *Strain vs time for IMC (uncorrected) and swelling.*

It is obvious from figure 2 and 3 that the slopes of strain for both conditions share the similarity of becoming linear eventually. Very distinct patterns can be seen when comparing the strains for shrinkage and swelling in from both figures. The slope of the shrinkage strain is almost entirely linear whereas the swelling strain shows gradual decrease in the slope steepness before eventually linear. This can be explained with regard to the FSP of the wood. The FSP of wood contain about 30%MC. The mechanical and physical properties of wood changes drastically only when it is below FSP. The MC of wood in the swelling and shrinkage condition i.e. oven dried and fully water saturated wood is 1.5% and 100%. Thus the swelling from 1.5%MC (which is far below FSP) would yield large deformation. On the other hand, theoretically the shrinkage from 100%MC (which is far above FSP) should not yield any deformation at all since it is already above the FSP.

However, it had been known that naturally wood cannot have the same value of MC throughout its entire structure. It is possible that small parts of the wood have MC below the FSP whereas other parts are above the FSP. Since the vacuum pump is in operation during shrinkage condition, it will pump out the moisture directly from the interior surface of the wood member. Thus, the interior areas will have MC below FSP while the outer parts have MC above FSP. Therefore, the strength of the interior part of the wood specimen will degrade. The interior of

the wood will contract gradually. This explains the gentle linear slope of the strain in the shrinkage condition.

Comparison can be made between the corrected and uncorrected DMC condition by observing the two slopes in figure 2. The corrected DMC condition is calculated by subtracting the effect of shrinkage. Figure 2 highlight that the slope of the linear portion of the uncorrected DMC is almost parallel to the shrinkage curve. This indicates that the increasing slope of the uncorrected DMC condition is due to shrinkage. The slope of the DMC condition has become stable horizontally after correction. This situation is similar for IMC condition. It can also be seen in figure 3 that the linear portion of the uncorrected IMC condition is almost parallel to the linear portion of the swelling graph. After correction, the slope of the IMC condition has settled to a stable value.
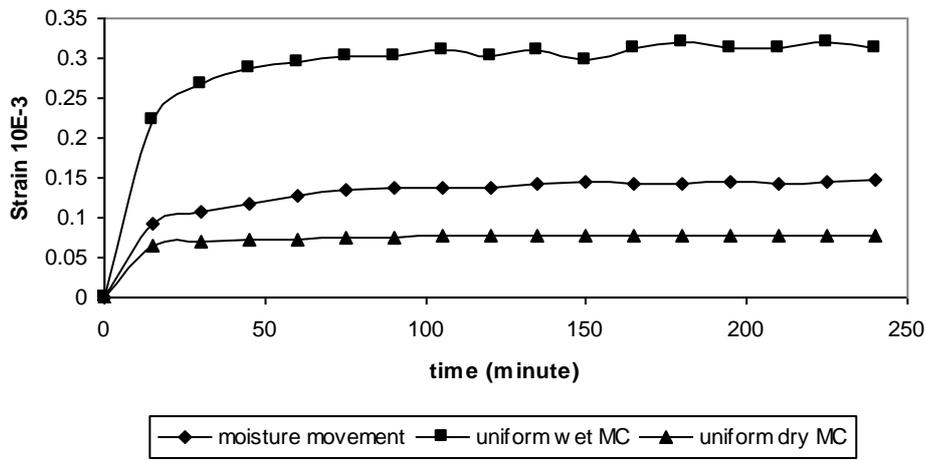

Fig. 4: *Strain vs time for moisture movement, uniform wet and dry MC.*

In figure 4, the magnitude of strain between the dry and wet MC condition is highly contrasting. The wet MC condition shows higher strain with a steep slope initially. Although the magnitude of strain in wet condition is higher it settles to a maximum value very quickly. This is consistent with existing theories where the stiffness or the modulus of elasticity decreases with increment in MC. The wet MC condition has weakened the structure of the wood member.
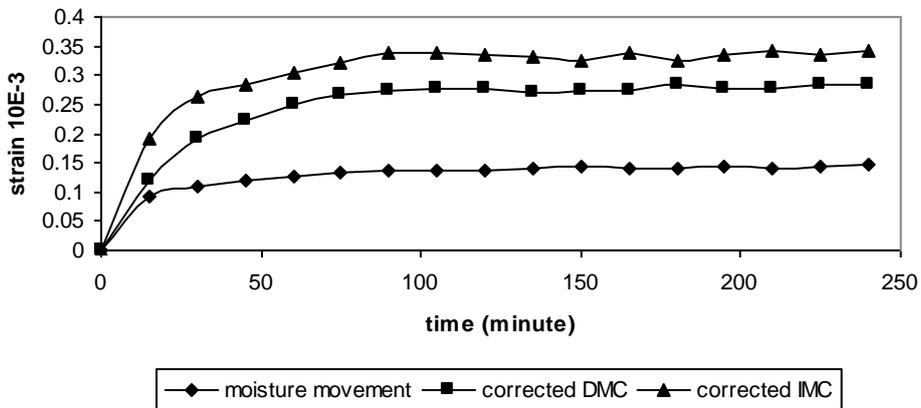

Fig. 5: *Strain vs time for moisture movement, corrected DMC and corrected IMC.*

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Figure 5 compares the strain for the corrected DMC, the corrected IMC and MM condition. It can be seen that the magnitude of strain in the corrected IMC is more than that of corrected DMC followed by the MM condition. A high magnitude in the strain indicates the MC change is continuously degrading the wood structure and will take a longer time for the strain to reach the maximum value. In the MM condition, although moisture does go through the wood specimen but the absence of MC change allows it to maintain its structure and strength.
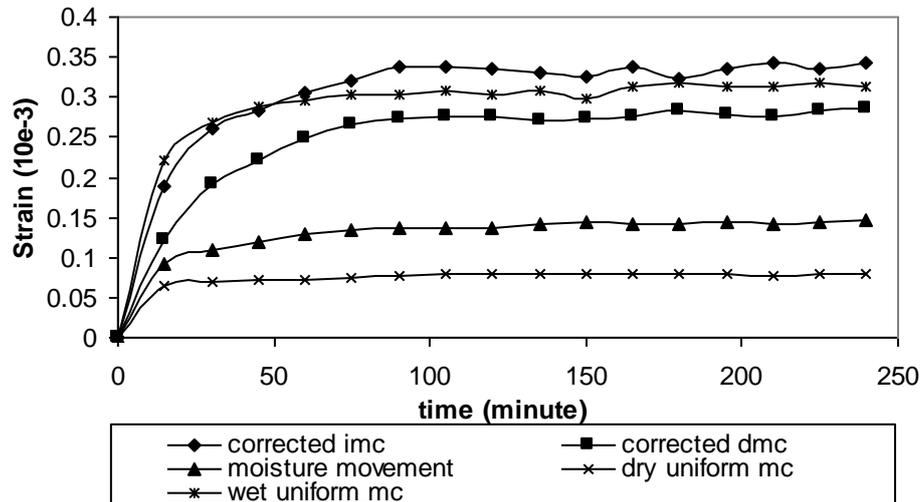

Fig. 6: *Strain vs time for all condition.*

Figure 6 shows the strain curves for all conditions. It shows that corrected IMC is highest followed by wet MC, corrected DMC, MM and dry MC. This proves that the MM alone will not result in greatly enhanced deformation. The simultaneous action of MM and MC change in a loaded wood specimen is required to cause this greatly enhanced deformation. MC change is required to provoke a change in the macromolecular structure due to volume change.

6.   CONCLUSIONS

The goals of the series of experiments are to compares compression loading effect in several conditions namely the moisture movement with MC changes i.e. IMC and DMC, moisture movement without MC change and conditions without moisture movement i.e. dry and wet uniform MC. It is found that moisture movement with MC change greatly enhances the deformation i.e. IMC yield greater strain than wet uniform MC and followed by DMC. Whereas moisture movement without MC changes least affected the deformations it is found to be still higher than the dry uniform MC. However, the rate of moisture movement has not been analyzed and thus it is not known whether a higher rate of moisture movement would have any effect on the deformation. More extensive experiments are required to conduct such tests. The condition of no moisture movement is used as a basis for comparison with other conditions because this condition is the ordinary creep or viscoelastic creep.

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