Flexural creep of structural flakeboards under cyclic humidity

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Abstract

Flexural creep behavior of randomly oriented structural flakeboards under cyclic humidity is presented. Specimens fabricated with 5 and 7 percent phenol-formaldehyde resin were subjected to constant concentrated load in bending under slow and fast cyclic relative humidity (RH) between 65 and 95 percent for 100 days. The temperature was set at a constant 75°F through the test duration and each humidity level was maintained for 33 days (slow cycle) and 2 days (fast cycle). Boards made with sweetgum flakes showed better creep resistance than those made of white oak. Significant effect on the creep resistance was observed when the resin content was increased from 5 to 7 percent under highly humid environments. Large deflections occurred and large permanent deformations remained for both groups after the relaxation. However, fast RH cycles had a greater weakening effect on creep resistance than did slow change. Creep moduli and relative creep, often considered to be the indices of the long-term performance of flakeboards, were significantly influenced by the change of RH. The resulting information may provide a better understanding of the long-term engineering performance of structural flakeboards as affected by the changes of RH conditions.

A major concern in the development and application of wood composites as building panel materials is their serviceability or lifetime performance, especially under severe environments. The structural applications of wood composite products could be improved if quantitative and reliable information concerning their long-term performance were available. Such information can be provided if the time-dependent load-carrying properties of wood composite materials under changing environments are fully understood.

The load-carrying capacity of a material is generally characterized by its viscoelastic behavior. Such information for solid wood has been well documented (3,5,10,11, 15,22-27), but only limited information is available for wood-based composite materials, especially hardwood flakeboard, waferboard and oriented strandboard. In the middle 1960s, Bryan and Schniewind (7) tested urea- and phenol-formaldehyde (PF) Douglas-fir particleboard to study their flexural creep behavior under constant and cyclic humidity conditions. They reported that no major differences were found between these two types of composite panels. However, it was indicated that the cyclic humidity treatments significantly increased the relative creep over those tested under constant humidity. Also, they suggested that effects of the sorption process on the viscoelastic behavior of particleboard may very well be a key for consideration in regard to the material's durability under exterior exposure.

The creep behavior of particleboard and hardboard under 14-day cycling conditions from 6 to 18 percent moisture content (MC) was studied by Armstrong and Grossman (4). They reported that large increases in beam deflections occurred at the first change of moisture, whether a gain or loss. In subsequent moisture changes, desorption of moisture caused further increases in deflection, whereas adsorption caused only small increases or even slight decreases in deflection. This suggests that the basic

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mechanism of the transient effects is similar among particleboard, hardboard, and solid wood (3,5,10,11,15,19). However, the quantitative difference observed in the creep behavior of these materials might be due to the nature of the bonding of the components.

A study of the flexural creep behavior of particleboard under 48-hour cyclically changing conditions from 40 to 80 percent relative humidity (RH) for 15 days was conducted by Haygreen et al. (14). Their conclusions were: 1) flexural creep behavior is very sensitive to high humidity; 2) much more creep was observed in the specimens when they were subjected to fluctuating RH conditions than in those tested under constant RH; and 3) flexural creep is linearly proportional to the applied stress below approximately 20 percent of the static bending strength. Therefore, they suggested that high RH and cyclic RH conditions should be considered in the future study of creep behavior of structural panel products. Commercial particleboards were tested for creep under cyclic RH conditions of 30 and 90 percent every 48 hours by Lehmann et al. (16). The boards with disk-cut flake faces had considerably less creep deflections than those fabricated with flakes prepared from a ring flaker; the boards with aligned face flakes can carry twice the loads with only slightly more creep deflections than those with random face flakes. McNatt and Hunt (18) investigated the creep behavior of thick structural flakeboards (1-1/8 in.) subjected to cyclic 48-hour RH conditions of 25 and 85 percent, and they reported that the creep deflection under cyclic humidity was 3 to 4 times higher than under constant humidity. However, the effect of the duration of RH cycles on the creep behavior of wood composite panels was not investigated.

More recently, the creep behavior of flakeboards made with a mixture of southern species (20% by weight of southern pine, sweetgum, red oak, white oak, and hickory) was investigated by Price (21). All the specimens were fabricated with a PF resin content (RC) of 6 percent and the range of RH was 50 to 85 percent. However, information related to RH levels higher than 85 percent and the effect of RC level on the creep of flakeboards was not evaluated. Furthermore, the durations of cyclic RH selected in that study were 4 days, 8 days, and 32 days and the total loading duration was only 32 days. As a result, the moisture changes due to the fluctuation of RH were relatively small and information regarding the effect of the sorption process on the creep behavior of flakeboards was limited.

The creep behavior of hardboard in tension was studied recently by Martensson and Thelanderson (17). Their tests showed a different creep pattern during the cycling condition from those reported in bending tests. The effect of MC on the creep of hardboard induced an abrupt change in strain at the beginning of each stage after shrinkage and swelling strain was eliminated. Based on the abovementioned information, creep behavior of wood composite materials may be very sensitive to the duration of cyclic RH, especially at high RH conditions. Therefore, for a better understanding of the effect of adsorption and desorption processes on the creep behavior of wood composites, specimens subjected to different durations of cyclic RH should be investigated.

The effect of resin type on the creep behavior of composite panels under constant environmental conditions has been intensively studied (1,6-9,12,13,16,20), however, the variability of results suggests that other process variables might play an important role. It is believed that the effect of different resin applications on the creep behavior of wood composites would be better defined when subjected to severe environmental conditions, such as high constant RH and temperature or cyclic RH of various durations.

The effect of resin level and RH on the creep behavior of structural hardwood flakeboard was recently studied by Yeh et al. (28). They reported no significant effect on the creep resistance when the RC was increased from 5 to 7 percent. However, the specimens were flexurally loaded under constant high (95%) and constant low (65%) RH at 75°F and no information concerning any cyclic RH effect was obtained. Therefore, the study described in this paper was designed to explore the effect of the duration of cyclic humidity on the flexural creep behavior of wood composite panel products. In addition, the influence of RC on creep behavior under cyclic humidity was investigated.

Materials and method

The flakes, approximately 3 inches long by 0.02 inch thick and of random width, were prepared by a laboratory model disk flaker from white oak (*Quercus alba*) and sweetgum (*Liquidambar styraciflua*) disks. The experimental design of panel fabrication in this study was chosen as follows:

1. Flake moisture: about 3 percent;
2. Resin type: liquid PF;
3. RC: 5 or 7 percent;
4. Press temperature: 350°F;
5. Panel dimension: 42 by 40 by 0.5 inches;
6. Total press time: 6 minutes;
7. Pressures and press times: 430 tons or 512 psi (2 min.) — 300 tons or 375 psi (2 min.) — 150 tons or 179 psi (1 min.) — 50 tons or 60 psi (1 min.) — 0 ton (release);
8. Panel density: 42 to 45 pcf (white oak) and 40 to 42 pcf (sweetgum), based on ovendry weight and volume at 65 percent RH;
9. Panel replication: 12.

A total of 48 sheets of randomly oriented flakeboards were laboratory fabricated for this study (2 species × 2 RC × 12 panel replications = 48). Creep and static bending specimens needed for this study were cut from each panel. The following experimental procedures were designed for the creep study:

1. Size of specimens: 3 inches wide and 18 inches long;
2. Number of replications: 6 for each combination of species, RC, and RH treatment;
3. Testing type: bending under concentrated load with a span of 16 inches;
4. Load level: 1/4 of the average modulus of rupture (MOR) of 5 percent RC white oak groups tested under static bending at both 65 and 95 percent RH, which were the weakest groups at both RH conditions;

5. RH treatments:

C1: All specimens were preconditioned and equilibrated under 65 percent RH at 75°F and then exposed to a slow cycle of 65-95-65 percent RH with a 33-day duration at each RH level;

C2: All specimens were preconditioned and equilibrated under 65 percent RH at 75°F and then exposed to fast cycles of 65-95-65 percent RH with a 2-day duration at each RH level;

6. Relaxation time: the specimens were relaxed 1 to 2 months after unloading under 65 percent RH at 75°F;

7. Measurement of deflection: the creep deflection and creep recovery in each specimen were measured with a dial gauge with accuracy of 0.001 inch.

Two walk-in environment rooms, with temperature and humidity controller, were utilized to hold the flexural creep testing frames and to condition specimens at designated RH and temperature. The creep testing frame capable of loading 24 specimens, equipped with dial gauges (0.001 in. increment) for creep deflection measurement, is pictured in Figure 1.

Results and discussion

Effect of RH level on bending strength

The MOR was determined by testing the specimens under centrally loaded static flatwise bending according to ASTM Standard D-1037 (2). Two groups of specimens were tested and each group contained 48 specimens (12 replications × 2 species × 2 resin contents). One group was conditioned and equilibrated under 65 percent RH at 75°F while the other was treated under 95 percent RH.

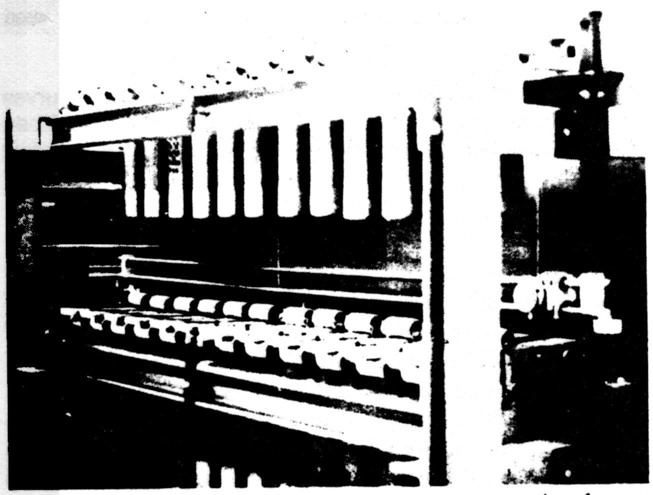

Figure 1. — Twenty-four-space flexural creep testing frame.

It is evident from Table 1 that sweetgum flakeboard had much higher bending strength (MOR) than the white oak specimens. Furthermore, the increase from 65 to 95 percent RH considerably reduced the MOR. Therefore, it could be expected that creep loading based on the MOR measured at 65 percent RH but imposed on specimens subjected to the cycle between low (65%) and high (95%) RH conditions may cause early failure of some specimens. Since this experiment was designed for the assessment of creep resistance and permanent deformation, but not the creep-rupture (duration-of-load) behavior of flakeboard, the situation of early failure had to be avoided. For this reason, the load level for all specimens in this study was chosen to be the average of one-fourth of the two mean MORs of the weakest groups, the white oak, measured at 65 and 95 percent RH.

Creep deflections and relative creep

The creep deflections and the values of relative creep prior to unloading are summarized in Table 2. There are three major viscoelastic related quantities given in Table 2, i.e., instantaneous deflection, creep deflection measured right before unloading, and permanent deflection. In addition, the values of relative creep for each group, expressed as the ratio of the difference between creep and instantaneous deflection to the instantaneous deflection, are included. The average MC measured in the C1 group (slow cycle) was approximately 11 and 21 percent for the periods of 65 and 95 percent RH, respectively. However, a much narrower range, 14 to 19 percent, was recorded in the C2 group (fast cycle).

In the C1 group, the creep performance of the two species types during the first period of 65 percent RH was very close to those being tested under constant 65 percent RH as reported in a previous study (28). The creep was sharply increased when the RH level was elevated to 95 percent and leveled off after 300 hours of 95 percent RH (Fig. 2). When the RH was changed back to 65 percent, creep deflection moderately increased during the first 3 days, then leveled off. As a result, very large permanent deflections were observed in all specimens after 1,000 hours of relaxation. This indicated that the creep resistance of flakeboard is significantly reduced when a slow cyclic RH of 65-95-65 percent is applied.

As shown in Figure 2, the sweetgum boards performed much better in creep resistance than the white oak group

TABLE 1. — *Flatwise bending strength (MOR) of flakeboards as affected by the RC and hygroscopic treatment at 75°F.*

Species	RC	Density[a]	MOR 65% RH Mean	MOR 65% RH SD[b]	MOR 95% RH Mean	MOR 95% RH SD	Reduction
	(%)	(pcf)	(psi)				(%)
White oak	5	42.4	2,084	720	814	260	61
	7	44.9	2,779	469	1,593	406	43
Sweetgum	5	41.4	3,280	999	1,950	383	41
	7	42.1	3,824	649	1,896	322	50

[a] Based on 65 percent RH at 75°F.
[b] SD = standard deviation.

TABLE 2. — *Summary of displacements (in.) of flakeboards for each group.*

Group	Species	RC	Instantaneous deflection	Maximum deflection prior to unloading[a]	Permanent deflection[b]	Maximum relative creep[c]
		(%)		(in.)		
C1	White oak	5	0.082	1.088	0.892	12.27
		7	0.085	0.840	0.671	8.88
	Sweetgum	5	0.075	0.667	0.522	7.89
		7	0.062	0.517	0.399	7.34
C2	White oak[d]	5	0.083	1.349	1.036	15.25
		7	0.095	1.548	1.161	15.29
	Sweetgum	5	0.065	1.009	0.778	14.52
		7	0.067	0.740	0.546	10.04

[a] Recorded immediately before unloading.
[b] Recorded after relaxed.
[c] Maximum relative creep = (maximum deflection/instantaneous deflection) − 1.
[d] Only three unfailed white oak specimens with 5 percent RC were considered in the evaluation.

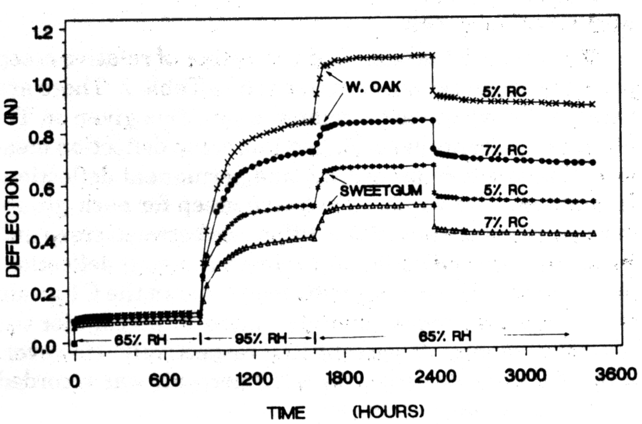

Figure 2. — Creep deflection and creep recovery time curves for flakeboards (C1) tested under a slow cycle of 65-95-65 percent RH (5% resin content (RC) vs. 7% RC; sweetgum vs. white oak).

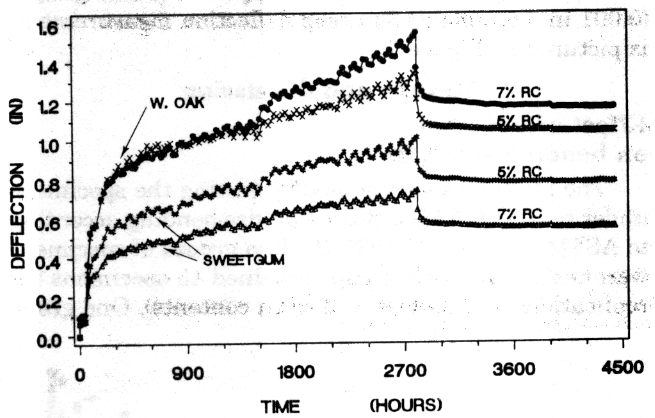

Figure 3. — Creep deflection and creep recovery time curves for flakeboards (C2) tested under a fast cycle of 65-95-65 percent RH (5% resin content (RC) vs. 7% RC; sweetgum vs. white oak).

during the period of 95-65 percent RH in the slow cyclic treatment of 65-95-65 percent RH. Moreover, the specimens fabricated with 7 percent RC showed better creep resistance during that period. The ratios of instantaneous recovery to instantaneous deflection of sweetgum and white oak boards were 1.39 and 1.48, respectively; only a unit value was observed in the constant 65 percent RH case as reported earlier (28). This indicates that the fatigue effect induced by the cyclic RH may have great weakening influence on the elastic recovery of the flakeboard. Due to the extremely large increase in creep deflection, the average values of relative creep in the C1 group (5 and 7% RC), measured right before unloading, of white oak and sweetgum boards were 10.58 and 7.62, respectively (Table 2).

Effect of the rate of RH changes

The effect of the rate of RH changes on the creep behavior of flakeboard is clearly demonstrated in the C2 group (Fig. 3), where the specimens were subjected to fast changes of RH (65-95-65% with 48 hr. at each RH level). It was found that the creep accelerated sharply during the first 100 hours and then leveled off slowly. In fact, three out of six white oak specimens in the 5 percent RC group failed after two cycles of 65-95-65 percent RH. This indicates that the fatigue effect induced by the hygrostresses developed during fast cycles of RH may be exceptionally large. Such an effect can weaken the adhesive bonds in the flakeboard considerably and cause the board's creep resistance to be significantly reduced. The increase and decrease of creep deflection during the desorption (95%-65% RH) and adsorption (65%-95% RH) cycle was evident in all specimens after 300 hours of loading, i.e., creep deflection increased during the low RH condition (65%) and decreased when switched to the high RH condition (95%). Overall, sweetgum boards had better creep resistance than white oak boards. It is apparent that the sweetgum boards fabricated with 7 percent RC of PF resin resisted creep much better than those with 5 percent RC. However, in the white oak group, only three specimens with 5 percent RC survived at unloading and obviously these specimens were stiffer and stronger. Thus, the average creep deflection calculated from the three unfailed white oak specimens fabricated with 5 percent RC was slightly higher than those observed from the group with

7 percent RC in which none of the specimens were ruptured during the creep tests. Furthermore, the effect of RC on the creep recovery was also evident in both species groups (Fig. 3). As expected, a much higher ratio of instantaneous recovery to instantaneous deflection was observed for the C2 group; the average values were 1.68 for the sweetgum boards and 1.82 for the white oak boards. Again, this suggests that the elastic recovery and permanent deformation will be significantly affected by the cyclic RH during the loading.

For comparative purposes, the results of those specimens tested under constant 65 and 95 percent RH as reported in a previous study (28) were plotted collectively with the results of C1 and C2 groups in Figures 4 and 5. The average values of relative creep of the white oak and sweetgum specimens in the C1 group prior to unloading (2,400 hr.) were approximately 15.67 and 16.20 times higher than those observed from groups subjected to constant 65 percent RH, respectively. However, considerably lower values, 2.66 and 2.23, respectively, resulted when the C1 group was compared with the boards tested under constant 95 percent RH. When the C2 group was compared with those subjected to constant 65 and 95 percent RH, moderately higher values, 22.62 (white oak), and 26.13 (sweetgum), and 3.84 (white oak), and 3.60 (sweetgum), respectively, resulted. These findings strongly suggest that the creep resistance of structural flakeboard is very sensitive to cyclic changes of RH, especially at a fast rate.

The effect of the rate of change in RH on the creep behavior was further studied by comparing groups between C1 and C2. It is evident from Figures 4 and 5 that the C2 group, regardless of species and RC, crept much more than those of the C1 group and had much higher permanent deflection. At 2,400 hours (just prior to unloading), the average relative creep of white oak boards in the C2 group was 1.44 times greater than those in the C1 group; for sweetgum, the C2 specimens had an average relative creep value 1.61 times greater than the C1 specimens. However, an almost equal percentage of increase in permanent deflection was observed in the sweetgum

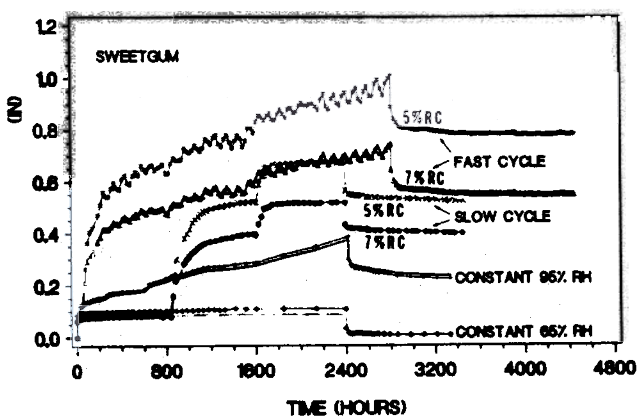

Figure 4. — Creep deflection and creep recovery time curves for sweetgum flakeboards (constant 65% RH vs. constant 95% RH vs. slow cycle (C1) of 65-95-65% RH vs. fast cycle (C2) of 65-95-65% RH).

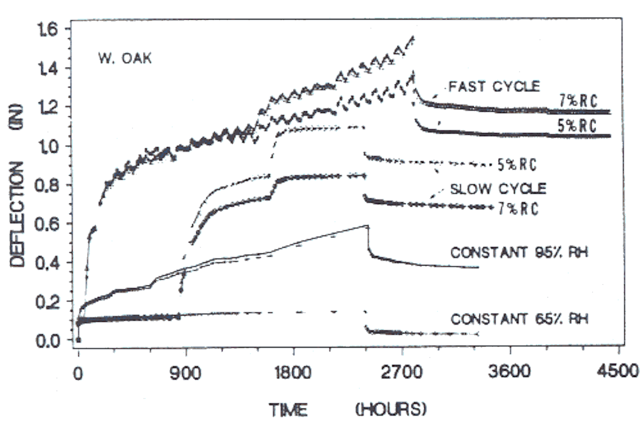

Figure 5. — Creep deflection and creep recovery time curves for white oak flakeboards (constant 65% RH vs. constant 95% RH vs. slow cycle (C1) of 65-95-65% RH vs. fast cycle (C2) of 65-95-65% RH).

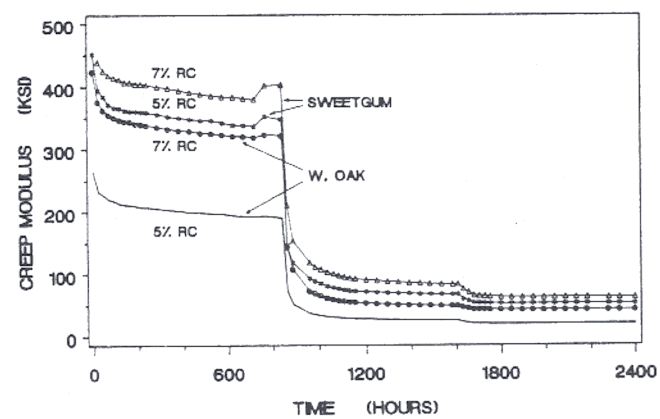

Figure 6. — Creep modulus as a function of time and RC of C1 group.

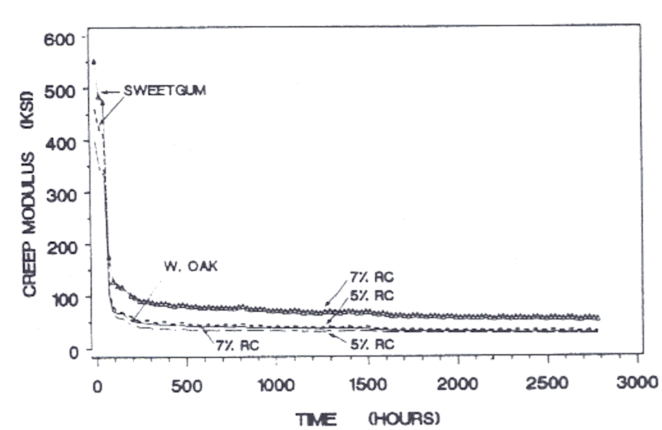

Figure 7. — Creep modulus as a function of time and RC of C2 group.

(44%) and white oak (41%) specimens in the C2 group. These results clearly imply that the long-term engineering performance, or service life, of flakeboards is substantially influenced by the level of RH and the speed of the fluctuation of RH in the service environments.

Permanent deflection

In the C1 group, average values of irrecoverable creep deflection (permanent deflection) measured in the white oak and sweetgum boards were 30.06 and 70.85 times higher than those previously tested under constant 65 percent RH, respectively. In the C2 group, values 42.25 and 102.62 times higher, respectively, were observed. However, much lower values, 2.16 and 1.88 (C1), and 3.04 and 2.72 (C2), correspondingly, resulted when compared to the case of the constant 95 percent RH group. These findings clearly indicate that the permanent deflection of flakeboards is significantly affected by a cyclic environment, especially at a fast rate and high level of RH conditions.

Creep modulus

The time- and moisture-dependent creep modulus of the tested specimens (generally considered to be an index that may be applicable to the prediction of the long-term load-carrying capacity of flakeboards (20)) was calculated by using the following equation:

$$E_c\,(t) = E_i/(1+R_c)$$

where:

E_i = elastic modulus (psi) measured from instantaneous deflection
R_c = relative creep = [deflection(t_1)/deflection(t_0)] − 1
t_1 = specific time between loading and unloading
t_0 = time when the load is applied

It is evident from Figures 6 and 7, in general, that the creep moduli of flakeboards dropped sharply after the first day of loading, and then decreased gradually as loading time increased until finally leveling off. The creep moduli of flakeboards of the C1 group gradually decreased under the period of 65 percent RH (first 792 hr.), but a sharp drop occurred when the RH was increased to 95 percent (Fig. 6). The magnitude of such a drop was considerably larger than those being measured from the instantaneous deflection (i.e., at the beginning of 65% RH), but a very small decrease was observed when RH was returned to 65 percent. An extremely huge drop of creep moduli occurred during the first 200 hours of loading in the C2 group, which was tested under the fast cycle of 65-95-65 percent RH, and it seems virtually no change thereafter until the test was completed (Fig. 7). Furthermore, creep moduli of all C2 group specimens calculated between 300 and 2,400 hours were very close in magnitude regardless of their species and RC. However, comparison between the creep moduli estimated at 0 hour and 2,400 hours revealed that boards fabricated with white oak flakes had lower retention of creep moduli than those made of sweetgum. The average retention of creep modulus in C1 and C2 groups at 2,400 hours is, respectively, only 11 and 8 percent. All of these findings suggest that a rapid increase in MC on the surface of the board, due to an abrupt increase in RH, significantly reduces creep modulus.

Conclusions and remarks

Regardless of the RC and the type of hygroscopic treatment, structural flakeboards fabricated with sweetgum flakes show better creep resistance than those made of white oak. Long-term engineering performance of flakeboards under changing environments can be moderately improved when PF RC is increased from 5 to 7 percent. The flexural creep behavior of flakeboards is very sensitive to high RH, especially when imposed in a cyclic fashion. Fast changes in cyclic conditions of 65-95-65 percent RH yielded an acceleration in creep over those subjected to a slowly changing rate of RH. This suggests that the creep behavior of flakeboards will be greatly influenced by the rate and duration of the sorption.

The creep moduli of flakeboards dropped sharply at the beginning of loading, especially when RH was suddenly increased or fast cyclic RH was applied, and further decreases were observed when RH changed. However, as time increased, such decreases and fluctuations due to the change of MC in the flakeboard were very small. These findings suggest that the long-term performance or service life of flakeboards will be strongly influenced by the level and rate of change of RH in the ambient building environments.

The results of this study provide further understanding of the creep behavior of flakeboards under changing RH conditions. Furthermore, such information may be useful to wood scientists/engineers in the development of engineering reliability models for the prediction of long-term performance of structural wood composite panel products under changing RH and to panel products industries for the improvement of their products for structural applications. However, information concerning how other environmental factors, such as high constant load level and temperature, and cyclic load and temperature individually or collectively associated with the changes of RH, affect the creep behavior and durability of structural wood composite panel products is still lacking. Investigations in these areas are currently underway and results will be reported in separate articles.

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