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Dimensional stability and creep behavior of heat-treated exterior medium density fiberboard

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Abstract A series of commercial phenol-formaldehyde bonded MDF panels were exposed to a post-manufacture heat-treatment at various temperatures and durations using a hot press and just enough pressure to ensure firm contact between the panel and the press platens. Physical properties and static flexural strengths of the post heat-treated MDF panels were evaluated according to ASTM D 1037 (2002). The results indicated that the post-manufacture heat-treatment of the exterior MDF panels resulted in improvement of thickness swelling. Water absorption and linear expansion properties were adversely affected by the heat-treatment. Modulus of rupture and modulus of elasticity values of the heat-treated panels decreased with increasing treatment temperature. A series of three 12-week creep tests were performed in climatic chambers conditioned at 65% RH, 90% RH, and cyclic 65–90% RH, all at a steady temperature of 20 °C. The creep tests generally followed procedures as specified in ASTM D 6815-02a (2002). Creep deflections of the panels increased with increasing temperature of the post heat-treatment.

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Dimensionsstabilität und Kriechverhalten von wärmebehandelten mitteldichten Faserplatten für den Außenbereich

Zusammenfassung Handelsübliche, Phenolformaldehyd verleimte MDF-Platten wurden nach der Herstellung mittels einer Heißpresse bei unterschiedlichen Temperaturen und Dauer wärmebehandelt. Dabei wurde nur soviel Druck ausgeübt, um einen festen Kontakt zwischen Platte und Plattenpresse zu erzeugen. Die physikalischen Eigenschaften sowie die statische Biegefestigkeit der wärmebehandelten MDF-Platten wurden gemäß ASTM D 1037 (2002) bestimmt. Die Ergebnisse zeigten, dass durch die nachträgliche Wärmebehandlung die Dickenquellung der MDF-Platten für den Außenbereich verbessert wurde, wohingegen die Wasserabsorption und Längendehnung negativ beeinflusst wurden. Die Biegefestigkeit und der Elastizitätsmodul der Platten nahmen mit steigender Behandlungstemperatur ab. Drei zwölfwöchige Kriechprüfungen wurden bei 65% rLf, 90% rLf und Wechselklima von 60–90% rLF und jeweils einer konstanten Temperatur von 20 °C in Anlehnung an ASTM D 6815-02a (2002) durchgeführt. Die Kriechverformungen nahmen mit steigender Behandlungstemperatur zu.

1 Introduction

Although medium density fiberboard (MDF) is sometimes bonded with heat and water resistant adhesives, such as phenol-formaldehyde (PF) and isocyanate resins, MDF is not generally recommended for exterior applications. The disadvantage of MDF compared to plywood is that when MDF has contact with water it generally swells more than

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plywood and a higher proportion of that swelling may not be recoverable after drying. This is resulting from two main factors: the inherent hygroscopicity of the wood fiber and the residual stresses created within the fiber mat during hot pressing. For these reasons, when the MDF panel has contact with water, the wood swells and some of that residual stress is released, causing an increase in the thickness of the panel. Excessive thickness swelling not only causes a poor appearance, but also markedly weakens panel products. As with other composites, MDF panels benefit from improved dimensional stability in applications where it may be subjected to changing moisture conditions. These applications are typically not life-safety applications. Semi-structural applications such as shelving could also benefit from heat-treatment that might impart enhanced resistance to permanent set or creep under longer-term loadings, especially when coupled with changes in ambient moisture.

Several studies have reported on the influences of the post heat-treatment of wood-based composite panels, such as particleboard, flakeboard, waferboard, and oriented strand-board (OSB) bonded with PF resin (Suchsland and Enlow 1968, Hsu et al. 1989, Zhang et al. 1997, Ohlmeyer and Lukowsky 2004, Del Menezzi and Tomaselli 2006, Okino et al. 2007). These studies often reported that the secondary thermal treatment reduced swelling, enhanced resistance of the wood-based panels to moisture absorption and enhanced durability and fungal resistance of materials. However, these studies generally reported that heat treatment had embrittled wood-based panels and decreased the bending strength and the stiffness of the panels. Heat treatment has also been reported to affect a host of other moisture dependent properties (Garcia et al. 2006, Winandy and Krzysik 2007). The treatment sometimes known as retification reduces equilibrium moisture content by permanently degrading the hemicelluloses being one of the major hygroscopic components of wood, and by volatilizing extractives or further breaking down other low-molecular weight polymers in the wood (Winandy and Krzysik 2007). Hsu (1986) developed a fast heat-treatment process for composite panels after panel pressing. That process was based on a direct contact post treatment at temperatures between 230 and 250 °C.

Specifically for wood-based panels, there are several methods of treatment or strategies to improve dimensional stability which can be divided into three different means of application: pre-treatment, post-treatment and production technology. In the second group methods applied to consolidated panel are found and direct thermal treatment is the most usual one (Del Menezzi and Tomaselli 2006). While contact post-treatments have become common practice in wet process hardboard manufacture, it is not commonly used in dry process MDF plants, but it could be introduced to impart specific properties to MDF panels. Also, post-manufacture thermal treatment could decrease the moisture content of MDF panels prior to shipping, thereby reducing weight and improving their dimensional stability.

Post manufacture heat-treated wood-based panels such as particleboard, waferboard, and flakeboard bonded with phenol-formaldehyde (PF) have been extensively studied. An extensive literature research did not reveal any information about the effects of post heat-treatment on dimensional stability and creep behavior of exterior MDF in cyclic environments while other physical and mechanical properties of MDF panels made from thermally treated fibers have been investigated by Garcia et al. (2006) and Mohebby and Ilbeighi (2007). Creep performance of materials in use as structural members is very important because they are subjected to load for a long period. There has been much research on the creep behavior of MDF (Kehr and Dube 1996, Niemz et al. 1997, Seco and Barra 1998, Pritchard et al. 2001, Boehme 1992, Zhou et al. 2001). However, there is no information on the creep behavior of heat-treated exterior MDF. The objective of this research was to investigate the effects of post-manufacture heat-treatment on the physical, mechanical and rheological properties.

2 Materials and methods

2.1 Commercial MDF panels

The MDF material used in this study was a commercially manufactured, 16-mm thick, PF-bonded, exterior, dry-process MDF panel used in the exterior siding and trim market. These MDF panels had been bonded with a phenol-formaldehyde resin and shipped without the coatings or primers typically applied for typical exterior applications. The commercial panels were made from furnishes of pine and beech species. Panels bonded with PF resin were chosen because PF resin is a more heat-resistant, exterior-type resin. It is commercially used in the fiberboard panel industry, but not as much as urea-formaldehyde (UF) resin. No wax was used for the panel manufacture. No UF-bonded MDF panels were chosen for this study because UF resin might have been degraded when exposed to the prolonged high temperature conditions of post heat-treatment. Thirty $120 \times 240\,cm^2$ commercial MDF panels were then cut into smaller test panels ($100 \times 100\,cm^2$). The sixty $100 \times 100\,cm^2$ test panels were then randomly assigned to experimental groups. An overview of the experimental design is given in Table 1.

2.2 Thermal treatment

The MDF panels were loaded into a heated press using a computer controlled single-opening hot press and were

Table 1 Summary of design of experiment
Tabelle 1 Versuchsdesign

Press platen temperature (°C)	Heat post treatment duration (min)	Heat-treated panel size (cm)[a]	Specimen replications: Flexural properties: Short-term tests (static MOR/MOE)[b]	Flexural properties: Long-term creep tests	Physical properties: TS/WA[b]	Physical properties: LE[b]
Control	–	100	48[c]	72[d]	30[e]	30[e]
175	15	×	48	72	30	30
200	30	100	48	72	30	30
225	30		48	72	30	30

[a] Panel replication: six panels for short term flexural tests and nine panels for long-term creep tests for each treatment level.
[b] MOR: modulus of rupture. MOE: modulus of elasticity. TS: thickness swelling. WA: water absorption. LE: linear expansion.
[c] Half (24) of the specimens were used for 20 °C/65 HR and other (24) were used for 20 °C/90 HR.
[d] 1/3 of the specimens (24) were used for 20 °C/65 HR, 1/3 (24) for 20 °C/90 HR, and 1/3 (24) were used for cyclic 20 °C/65–90 HR.
[e] There were 12 specimens obtained from panels assigned to static testing and 18 from panels assigned to creep testing for a total of 30.

thermally treated at platen temperature of 175 °C for 15 min, 200 °C for 30 min or 225 °C for 30 min. The press-control system included specially designed temperature/gas pressure probes for measuring internal panel temperature and gas pressure during pressing. To insert the probe, a small hole (5 cm length) was drilled in the center core of each manufactured panel. The temperature/gas pressure probe was then inserted into this hole to measure the panel temperature and gas pressure variation during post-manufacture thermal treatment.

A platen contact pressure of 150 (kPa) was applied to provide light but uniform contact between press plates and the panels' surfaces. To demonstrate that the process did not constitute a fire hazard, several 16 mm thick panels were prepared and heated for 30 min at 225 °C. After heat treatment, all panels were cooled prior to stacking to further minimize fire hazards. A total of sixty $100 \times 100\ \mathrm{cm}^2$ panels (60), 24 for short-term flexural tests (six panels for three treatments and control) and 36 for long-term creep tests (nine panels for three treatments and control), were treated. Eight flexural testing specimens, two thickness swelling/water absorption specimens, and two linear expansion specimens were taken from each treatment panel. Panel densities were measured on the specimens used for thickness swelling tests.

For physical and mechanical tests, all multiple comparisons were first subjected to an analysis of variance (ANOVA) at $p < 0.01$ and significant differences between mean values of untreated and treated MDF specimens were determined using Duncan's multiple range test.

2.3 Physical properties

Physical properties, such as density, thickness swelling (TS), water absorption (WA), and linear expansion (LE) were performed in accordance with ASTM D 1037-02 (2002). To evaluate physical properties, thirty specimens (12 specimens obtained from panels assigned to static testing and 18 from panels assigned to creep testing) were cut from the experimental panels for TS, WA, and LE tests. WA and TS evaluations were made after two hours and 24 h of soaking. LE, TS, and WA were calculated on the basis of the initial dimensions and weights. LE was determined by measuring the change in length of the specimen with dimensions of 76 mm wide and 304 mm long. The length of each specimen was then measured to the nearest 0.01 mm using equipment according to ASTM D 1037. WA and TS tests were performed on the same specimen with dimensions of $152 \times 152\ \mathrm{mm}^2$.

2.4 Flexural testing of the MDF panels

2.4.1 Short-term flexural testing

ASTM D 6815-02a (2002) specifies span-depth ratio of greater than 48 : 1, overall span greater than 768 mm, based on a panel thickness of 16 mm. Specimen size could then be $100 \times 800\ \mathrm{mm}^2$. Supports and load points had a virtual diameter of 50 mm. Loading points were one-third of the span length (third-point loading) with a rate of loading sufficient to produce flexural failure at approximately one minute. The basic static testing principles and procedures of ASTM D 1037 for wood-based panel products were used to develop this portion of the ASTM D 6815 procedure. Two temperature/relative humidity (RH) conditions were used for conditioning and testing (20 °C/65% RH and 20 °C/90% RH). Twenty-four specimens (four from each of the 6 panels/treatment) from each heat-treatment group and at each temperature/RH condition were evaluated for static modulus of rupture (MOR) and modulus of elasticity (MOE). The tests were conducted using an Instron Universal Testing Machine at a crosshead speed of 7.7 mm/min.

2.4.2 Long-term flexural creep testing

The general principles of ASTM D 6815-02a (2002) were used for the test procedures of this study. This procedure was established to predict the duration of load and creep experienced by viscoelastic materials like lumber and wood-based panels. This procedure is not intended to evaluate the performance of products under impact loading. In this study, smaller than minimum D 6815-recommended sample sizes were used due to our goal of determining relative fractional deflections rather than expressly defining the deflection/creep rates of each material. Identical span, environmental conditions, and load-head and support configurations as used for short-term flexure tests were used in creep testing. All long-term loadings were done with dead weights regardless of the environmental condition (i.e. the load is the same regardless of the environmental condition). Target loading levels were 7 to 10% of ultimate load at 65% RH and 10 to 15% of ultimate load at 90% RH environments. The load levels were near the ratio of design load to average ultimate load for other wood products. Deflection measurements taken (at a minimum) after load application (approx. 10 s after initiation of loading), one hour, day 1, day 3, day 7, and each week thereafter up to 12 weeks). The creep deflection at each evaluation period was measured with a dial gauge with an accuracy of 0.01 mm. The relative fractional deflection (RFD) of the treatment groups, Eq. 1, was then calculated from this creep data for the 12-week test period. The RFD(t) (also known as the creep factor) is defined as the ratio of difference between the deflection (a_t) measured at time $t$and the instantaneous deflection (a_o)

$$\mathrm{RFD(t)} = (a_\mathrm{t} - a_\mathrm{o})/a_\mathrm{o}. \qquad (1)$$

A series of three 12-week creep tests was performed in climatic chambers conditioned at either 65% RH, 90% RH, or cyclic 65–90% RH with a steady temperature of 20 °C. The cyclic conditioning consisted of 3.5 d at 65% RH, followed by 3.5 d at 90% RH for the full 12-week test period as specified in ASTM D 6815 (2002). At each humidity level, twenty-four specimens from each treatment group were used for measuring creep deflection and then calculating RFD (Table 1).

3 Results and discussion

3.1 Dimensional stability

Physical and mechanical test values of the heat-treated MDF specimens are presented in Tables 2 and 3, respectively. No differences in density resulted from the three heat-treatment levels when compared to control specimens. Statistical analysis found some significant differences ($\mathrm{pr} < 0.01$) between some group means for TS, WA, and LE values. Sig-

Table 2 Results of physical properties of the heat-treated MDF specimens
Tabelle 2 Physikalische Eigenschaften der wärmebehandelten MDF-Platten

Heat-treatment level	Specimen density (g/cm³)	Thickness swelling (%)		Water absorption (%)		Linear expansion (%) (50–90%)
		2	24	2	24	
Control	0.81 (0.02) A	1.08 (0.11) B[a]	4.71 (0.18) A	1.65 (0.53) A	6.85 (0.15) D	0.28 (0.03) B
175 °C–15 min	0.78 (0.01) A	1.24 (0.15) A	4.64 (0.29) A	1.68 (0.40) A	7.19 (0.16) C	0.29 (0.02) B
200 °C–30 min	0.80 (0.02) A	1.07 (0.11) B	4.36 (0.16) B	1.55 (0.78) B	7.80 (0.11) B	0.28 (0.03) B
225 °C–30 min	0.79 (0.02) A	1.00 (0.21) B	4.02 (0.27) C	1.60 (1.19) AB	8.81 (0.19) A	0.32 (0.03) A

[a] Groups with same letters in column indicate that there is no statistical difference ($p < 0.01$) between the samples according to the Duncan's multiply range test. Values in parentheses are SDs.

Table 3 Results of short-term flexure testing for variously heat-treated MDF
Tabelle 3 Ergebnisse der Kurzzeit-Biegeversuche unterschiedlich behandelter MDF-Platten

Heat-treatment level	Relative humidity (RH) (%)	Equilibrium moisture content (EMC) (%)	Modulus of rupture (MOR) (N/mm²)	Modulus of elasticity (MOE) (N/mm²)
Control		7.2 B	20.7 (0.99) A[a]	2895 (176) A
175 °C–15 min		7.6 A	19.8 (0.94) B	2679 (141) C
200 °C–30 min	65	7.4 AB	19.3 (1.03) C	2780 (164) B
225 °C–30 min		6.4 C	17.7 (0.96) D	2757 (157) CB
Control		11.7 A	15.2 (0.96) A	2095 (148) A
175 °C–15 min		11.3 B	15.4 (1.14) A	2037 (132) A
200 °C–30 min	90	11.0 B	15.5 (0.98) A	2135 (125) A
225 °C–30 min		9.9 C	14.2 (0.64) B	2126 (133) A

[a] Groups with same letters in column indicate that there is no statistical difference ($p < 0.01$) between the samples according to the Duncan's multiply range test. Values in parentheses are standard deviations.
Note: MOE was not affected by any heat-treatment temperature when evaluated at the 90% RH level.

nificant differences between groups were determined individually for these tests by Duncan's multiple-comparison tests (Table 2).

The thickness swelling values of the heat-treated specimens after 24-h water immersion varied from 4.71 to 4.02%. The lowest TS value with 4.02% was obtained from the specimens exposed to the highest treatment temperature (225 °C). The heat-treated specimens at $\geq$200 °C showed a significant reduction in thickness swelling after 24-h water soaking. Based on American National Standard ANSI-A208.2, maximum TS requirement for grade 160 MDF (representing the best properties) for interior applications is 10% (ANSI-A 208.2 2002). While all control and heat-treated specimens easily meet this TS requirement, the heat-treated MDF specimens at all three of the secondary heat-treatment levels (175, 200, and 225 °C) improved TS performance relative to the non-treated controls.

On the other hand, increasing heat-treatment temperature did not improve water absorption of the specimens. The specimens treated at 225 °C gave the highest WA value with 8.81%. These results were consistent with the results obtained in previous studies (Del Menezzi and Tomaselli 2006, Winandy and Krzysik 2007, Mohebby and Ilbeighi 2007). Similar results were also reported by Paul et al. (2006) for OSB made from heat-treated chips.

WA was clearly not a good predictor of dimensional stability as estimated by TS results for heat-treated MDF and these results suggest that WA is not controlled by the same physical characteristics as is TS. Winandy and Krzysik (2007) suggested that the absorbed water may have occupied void space and was therefore not directly associated with the fiber so it did not promote swelling. Vernois (2007) stated that wood treated at high temperature had less hygroscopicity than natural wood, but the material presented a certain porosity and when dipped in water it could absorb more than 20% of water. They also said that when dried again this absorbed water could be removed quite easily. Such behaviour is of importance for building materials.

Similar to WA, the LE values of the specimens were not improved by post heat-treatment. The LE values of the specimens treated at the two lower temperature heat-treatment levels did not show any significant differences when compared to the untreated specimens, while a significant difference in LE was noted for the 225 °C treatment. The highest LE value with 0.32% was obtained from the panel group exposed to 225 °C. This result was consistent with a previous study related to MDF panels made from heat-treated fibers (Garcia et al. 2006). All of the specimens heat-treated at 175 and 200 °C temperatures satisfied maximum LE requirement (0.3%) for all MDF specified in ANSI-A208.2, while those treated at 225 °C did not.

The reduction of the thickness swelling could be related to the chemical modification in the fiber cell walls during the heat-treatment. As the hemicelluloses are very hydrophilic compounds, their alteration could affect the dimensional stability in the boards (Yildiz and Gumuskaya 2007). Hemicelluloses are hydrolyzed during heat treatment and decreased the hygroscopity of heat-treated fiberboard (Winandy and Smith 2006). Exposure duration and temperature are two important factors affecting hemicelluloses degradation. Cumulative thermal exposure in the hot-press alters the hemicelluloses structure because arabinan and galactan, each a side-chain component of the hemicelluloses, tend to be more degraded as both temperature and press duration increase. These changes in the chemistry of hemicelluloses seem to reduce the hygroscopicity of the MDF fiber (Winandy and Krzysik 2007). The moisture absorption could also be suppressed due to increased cellulose crystallinty, degradation of the amorphous regions in the cellulose microfibrils or because fewer hydroxyl groups exist after the hydrothermal treatment. Cross linkings between the cell wall polymers, especially lignin, esterification between the cellulose microfibrils, and the formation of ether linkage by the splitting of two adjacent hydroxyl groups are other viable reasons for the swelling loss (Tjeerdsma and Militz 2005, Boonstra and Tjeerdsma 2006). Del Menezzi and Tomaselli (2006) reported that TS reduction was due to the compression stress release and because the heat-treatment changed the panel's hygroscopicity. They also stated that when the wood was heated above a certain temperature the polymers, mainly lignin, reduced the stiffness, and the compression stress could be released and rearranged within the consolidated fiber matrix while the heating treatment is applied.

3.2 Equilibrium moisture content (EMC)

The EMC of variously heat-treated MDF specimens in each exposure condition are shown in Table 3. The EMC of the MDF specimens were generally not affected by post heat-treatment temperatures of < 200 °C. This effect was consistent under both exposure conditions. However, heat-treatment temperatures of 225 °C significantly reduced ($p < 0.01$) the EMC by 6.4% at 65% RH and by 9.9% at 90% RH when each was compared with its respective untreated control group. This reduction is very advantageous and it means that the panels should be more stable in variable environmental conditions.

High temperatures used in manufacturing cellulosic fiberboards and hardboards decrease the hygroscopicity of the wood fibers. Thus, the EMC of these wood fibers is lower than that of solid wood, particularly at higher humidities (Myers and McNatt 1985). Equilibrium moisture contents (EMC) of the heat-treated MDF specimens exhibited a further decrease with increased exposure treatment temperature. Del Menezzi and Tomaselli (2006) and Winandy and Krzysik (2007) each reported that the reduction of EMC could happen because of the hemicelluloses, one of the more hygroscopic polymers within the cell wall and also generally the most heat sensitive polymers of the wood components. Since the density values of the treated panels did not significantly change much as seen in Table 2, the chemical degradations were minimal. It was estimated that irreversible loss of bound water could make the panels more hydrophobic.

3.3 Modulus of rupture and modulus of elasticity

The short-term (i.e., static) flexural properties of variously heat-treated MDF specimens under each exposure condition are shown in Table 3. The flexural properties of the MDF specimens, static MOR and MOE, were generally affected by post heat-treatment, but this effect was strongly influenced by the exposure condition (i.e. RH). This interaction between the two main effects (level of heat-treatment and exposure condition) was statistically significant ($p < 0.01$) for both MOR and MOE. Thus, when the effects of heat-treatment on the MOR and MOE of MDF are discussed, these effects must be considered independently for the two exposure conditions (65 and 90% RH). Treatment groups showing significant differences ($p < 0.01$) were determined according to the Duncan's multiply range test (Table 3).

The MOR values of the heat-treated specimens conditioned at 90% RH were lower than those conditioned at 65% RH. The lowest MOR value with 14.2 N/mm^2 was found for 225 °C at 90% RH. The MOR of MDF heat-treated at 225 °C decreased 14 for 65% RH, but only 7% for 90% RH when compared to untreated controls. While the MOR values of the specimens in the constant 65% RH showed significant loses with the increasing treatment temperature in static bending strength, those exposed at the constant 90% RH did not experience any strength loss when each was compared to its respective untreated control group.

In general, MOE was not affected to the same degree as was bending strength. Nor, were the effects of exposure condition on MOE identical. MOE was not affected by any heat-treatment temperature when evaluated at the 90% RH level (Table 3). Whereas, MOE was significantly reduced by 4–7% at all three levels of heat-treatment when evaluated at the 65% RH level. All control and heat-treated specimens conditioned at 90% RH met minimum MOR (14 N/mm^2) and MOE (1400 N/mm^2) requirements for grade 120 MDF specified in ANSI-A208.2. As for the specimens conditioned at 65% RH, the MOR values complied with requirement for grade 120 MDF while the MOE values satisfied grade 140 MDF.

In many ways, these results agree with past experience in that increasing heat-treatment temperature in the MDF specimens caused greater reduction of the MOR and MOE values compared to untreated specimens. This could be partly attributed to the fact that the heat treated MDF panels had some minor mass loss during heating. Stamm (1956) reported that softwood specimens heated over 30 min in air at 200 °C could loose 10% of their original MOR. Loss of MOR and MOE in wood was reported by different authors (Yildiz et al. 2006, Bengtsson et al. 2002, Kubojima et al. 2000) and heat-treated composites (Sundqvist et al. 2006, Ohlmeyer and Lukowsky 2004, Paul et al. 2006). The loss in mechanical properties could be related to the formation of soluble acidic chemicals; such as formic acid and acetic acid, from the hemicelluloses degradation (Garrote et al. 2001, Sundqvist et al. 2006). Those acids accelerate depolymerization of the carbohydrates by breaking down the long-chain carbohydrates to shorter chains. Depolymerization and shortening of the cellulose polymer could affect MOE and MOR of wood. It is known that acidic conditions at elevated temperature can degrade wood by hydrolysis and affect the wood strength (Rowell 2005).

3.4 Flexural creep behavior

The flexural creep behavior for the treated MDF specimens was evaluated for three exposure conditions (65% RH, 90% RH, and a cyclic 65–90% RH) at 20 °C. This creep data is summarized over the entire 12-week exposure period in Fig. 1a–c. It is critical to mention that no creep-rupture condition was encountered on any of the specimens over the 12-week test. The MDF panels experienced greater creep deflections at higher heat-treatment temperatures under the same environmental condition levels. Also, with respect to magnitude of creep deflection, little difference in creep between the two steady-state RH exposures was observed (Figs. 1a and 1b). However, this was certainly not the case for creep with the cyclic humidity exposure (Fig. 1c). The cyclic condition testing resulted in a level of creep deflections 2 to 3 times the deflections at 65% steady-state conditions at the end of the 12-week exposure. In many situations where wood is subjected to applied stress and moisture content change, the wood undergoes a mechano-sorptive creep due to an interaction between stress and moisture content change. This may result in great deformation compared to constant moisture content (Zhou et al. 2000). Creep deflections in the treated MDF specimens also increased with increasing relative humidity. Researchers had previously observed that changing relative humidity above 65% resulted in a higher creep deformation in wood-based panels (Laufenberg et al. 1999, Zhou et al. 2001, Pritchard et al. 2001). During moisture cycling, the first adsorption caused an increase in the deformation compared to constant

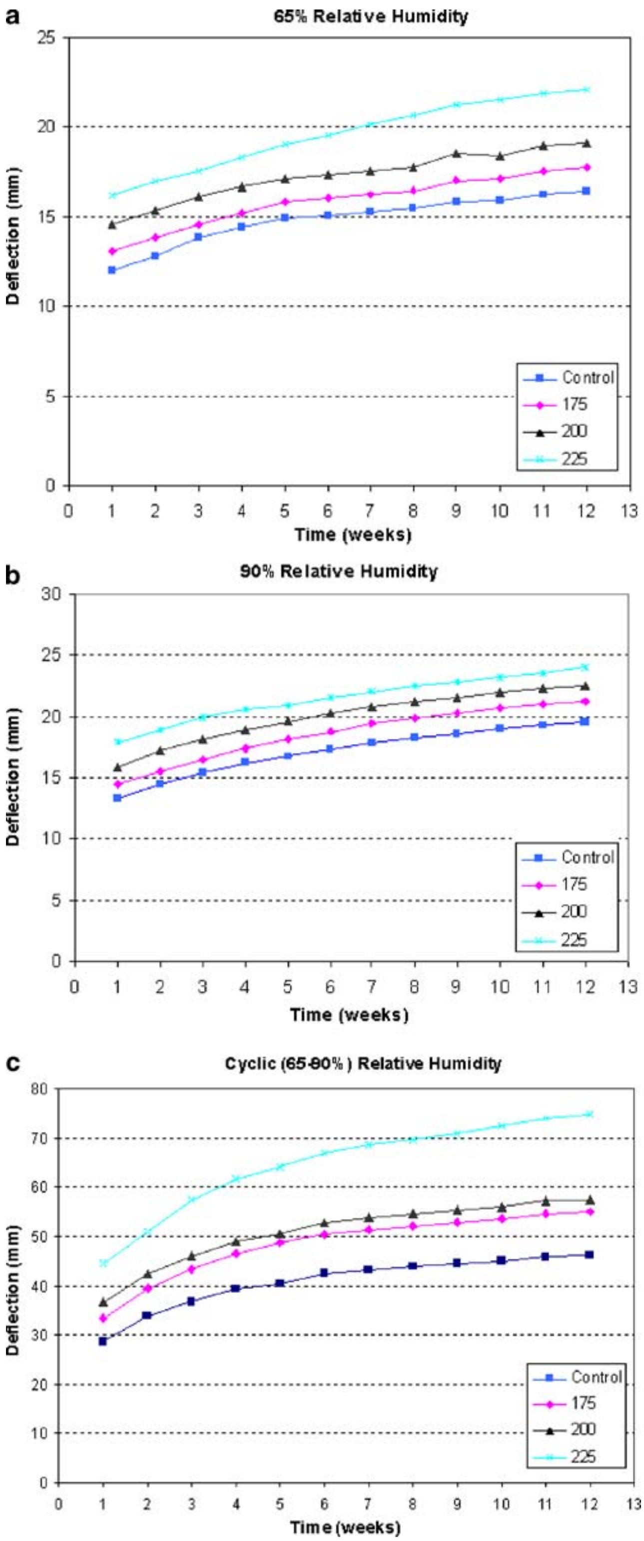

Fig. 1 Comparison of creep deflection curves for heat-treated and untreated MDF panels under (**a**) 65% RH condition at 20 °C, (**b**) 90%RH condition at 20 °C and (**c**) cyclic humidity (65–90% RH) at 20 °C

Abb. 1 Vergleich der Kriechverformung unterschiedlich wärmebehandelter und unbehandelter MDF-Platten bei (**a**) 65% rLf und 20 °C (**b**) 90% rLf und 20 °C und (**c**) Wechselklima (65–90% rLf) und 20 °C

moisture content. An increase in humidity causes swelling and thereby a larger moment of inertia, which may partly compensate for the weakening of the material due to moisture uptake (Epmeier et al. 2007).

The curves for calculated average relative fractional deflection (RFD)-time (the average initial (1-week) and final (12-week) for each type of the panel are plotted in Fig. 2a–c. The RFD values (also known as the creep factor) of the MDF specimens exposed at 65 RH, 90 RH, and cyclic 65–90% conditions increased with increasing treatment temperature. The RFD values of the specimens showed significant differences. The highest average creep deflection with 6.99% was obtained from the specimens treated at 225 °C and then exposed to cyclic (65–90% RH) condition. The combined effect of heat-treatment and elevated or cyclic relative humidities resulted in a significant increase in the RFD values compared to the untreated control specimens.

The creep deflections of the MDF specimens were significantly affected by post heat-treatment temperatures of $> 200\,^{\circ}C$. The physical state of wood amorphous polymers changes from glassy to rubbery when they are heated to the glass transition temperature. Much of the creep (deformation due to an interaction between stress and moisture content change) is due to molecular mobility in the amorphous region. As a result, molecules or flowing segments in wood substances have mobility; and under external stress, relative displacement between segments may arise, resulting in appreciable deformation in the wood (Zhou et al. 2000). Furthermore, higher creep deflections of the MDF specimens exposed to the cyclic relative humidity condition could be partly caused by deterioration of the inter-particle bonding in the MDF panels. The cured PF resin between fibers in the MDF specimens is deformed by changing humidity variation; this could eventually overstress some PF bonds, resulting in less cohesion and more creep. During relative humidity cycling, thickness and linear variations in MDF result in deterioration of the inter-particle bonding between the fibers (Ayrilmis 2007). Consequently, deterioration of the inter-particle bonding plays a role in increasing the creep deflections of the post-treated MDF specimens.

There is also the possibility of using color to estimate the brittleness of heat-treated wood (Phuong et al. 2007). Some darkening of the MDF specimen surfaces was observed as a result of secondary heat-treatments. The darkening on the specimen surfaces increased gradually depending on the treatment temperature ranging from 175 to 225 °C. In our experience, it can be said that heat-treatment generally induced darkening. But our experience was that darkening while a somewhat weak indicator in estimating the static flexural strength of the post heat-treated MDF panels is not entirely relieable.

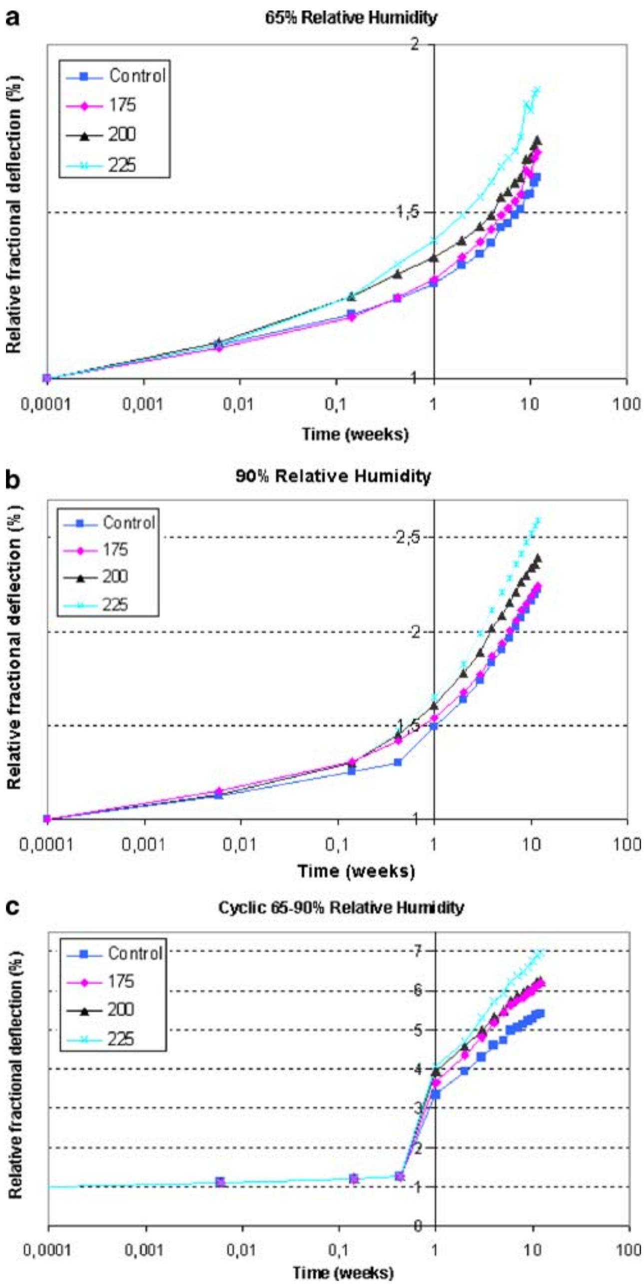

Fig. 2 Comparison of relative fractional deflection curves for heat-treated and untreated MDF panels under (**a**) 65% RH condition at 20 °C, (**b**) 90% RH condition at 20 °C and (**c**) cyclic humidity (65–90% RH) at 20 °C

Abb. 2 Vergleich des Kriechfaktors unterschiedlich wärmebehandelter und unbehandelter MDF-Platten bei (**a**) 65% rLf und 20 °C, (**b**) 90% rLf und 20 °C und (**c**) Wechselklima (65–90% rLf) und 20 °C

4 Conclusions

Post heat-treatment of exterior MDF is an effective method to reduce thickness swelling without great effect on flexural properties. However, water absorption properties were adversely affected by the heat-treatment. As the heat-treatment temperature used to treat commercially made MDF increased, the equilibrium moisture content and static flexural strength decreased. The change in flexural strength was proportionately more severe for the 65% RH testing than for the 90% RH test of flexural strength. Creep deflection for MDF panels was found to be highly sensitive to both post-treatment temparature levels and the severity and type (constant or cyclic) of environmental conditions used. Creep deflections of the panels increased with increasing heat-treatment temperature. Little difference was noted between creep and creep rate at the two steady-state RH exposures. However, the creep deflection of MDF specimens exposed to cyclic 65-to-90% RH conditions was much greater than for specimens exposed to constant humidity.

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