Wood Sci Technol (2011) 45:315–330
DOI 10.1007/s00226-010-0329-3

ORIGINAL

Thermal degradation of bending strength of plywood and oriented strand board: a kinetics approach

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Received: 19 May 2009 / Published online: 10 April 2010

Abstract The construction industry has relied heavily on wood and wood-based composites, such as oriented strand board (OSB) and plywood for timber frame construction. Therefore, it is highly imperative to categorize the response of wood-based composites when exposed to elevated temperatures for a sustained period of time. The essence of fire-resistant structural design is to ensure that structural integrity be maintained during and after the fire, prevent collapse and maintain means of egress. Another aspect is to assess post-fire structural integrity and residual strength of existing structure. The objective of this project was (a) to study the effect of exposure time on bending strength (MOR) of OSB and plywood at elevated temperatures, (b) to interpret any relationships between different temperature and time of exposure using a kinetics model for thermal degradation of strength, and (c) to develop a master curve representing temporal behavior of OSB and plywood at a reference temperature. As much as 1,152 samples were tested in static bending as a function of exposure time and several temperatures. Strength (MOR) of both OSB and plywood decreased as a function of temperature and exposure time. These results were fit to a simple kinetics model, based on the assumption of degradation kinetics following an Arrhenius activation energy model. The apparent activation energies for thermal degradation of strength were 54.1 kJ/mol for OSB and 62.8 kJ/mol for plywood. Furthermore, using the kinetics analysis along with time–temperature superposition, a master curve was generated at a reference temperature of 150°C which predicts degradation of strength with time on exposure at that reference temperature. The master curves show that although plywood has a higher initial

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strength, OSB performs better in terms of strength degradation after exposure to elevated temperature.

Introduction

Wood-based composites, such as oriented strand board (OSB) and plywood, are the main structural composite panels both in residential and in commercial timber construction. Walls and partitions are usually framed with solid sawn lumber (SSL) studs. Plywood and OSB are used as structural sheathings. OSB is also widely used as the web in I-joists. The use of wood-based composites in low-rise, single-family dwellings is increasing. As a result, they represent an increasing share of the wood products market (White and Winandy 2006). OSB has taken a major market share from plywood during the last two decades and still is driven by strong demand (APA 2005). With this increased use of wood composites, it becomes important to assess their fire performance and integrity after exposure to elevated temperatures (Grundahl 1992). Because they are less massive than solid timber, they are less likely to resist a rapid temperature rise (Cramer and White 1997). Hence, more study on the effect of elevated temperature on various properties of wood-based composites is needed. Such thermal degradation studies involve understanding and predicting wood-based materials' behavior during and after exposure to elevated temperatures.

Untreated plywood has a long history in service as roof sheathings. The introduction of fire retardant treated (FRT) plywood for roof sheathings allowed the building codes to accept FR-treated plywood roof sheathing as a replacement for non-combustible decking in some multifamily structures. In the past decade, however, a number of roof failures have occurred in structures using FRT plywood (APA 1989a). These failures were attributed to thermal degradation (Winandy et al. 1991) at service temperatures, which can reach up to 80°C (APA 1989b). Temperature has been shown to be a primary factor in strength loss of FRT wood (Gerhards 1982; Winandy et al. 1988). In these tests, both FRT plywood and untreated controls were exposed to temperatures ranging from 0 to 80°C. The test results for controls showed an initial slight increase (4%) in bending strength value as exposure time increased (Winandy et al. 1991). At 77°C, the strength degrades, but does not degrade much on exposure beyond 21 days. In contrast, FRT plywood loses about half its bending strength when exposed to 77°C for 63 days. This study reported that an increase in moisture content causes the degradation rate to increase. The strength degradation rate depends on exposure temperature and generally decays at a constant rate for fixed exposure conditions (Winandy et al. 1991). The strength degradation rates at higher temperatures are expected to be higher, but have not been investigated.

Other than FRT plywood, few studies have been conducted on changes in mechanical properties of OSB or untreated plywood at or after exposure to elevated temperatures (100–200°C). Due to the increased use of OSB and plywood in construction, it is important to undertake such studies. Fire is a special design case as it is not a loading condition for structures, but instead an environmental condition

that can have dramatic effects on the load carrying capacity of a structure (Cramer and White 1997). The main objective of fire-resistant structural design is to ensure that structural integrity is maintained during and after the fire. Furthermore, post-fire concerns include whether the structure has enough residual capacity to withstand the stresses in service during the course of its lifetime and can be reused, or whether all or part of the structure has to be rebuilt. Evaluation of the post-fire structural integrity and residual strength capacity will facilitate this decision-making process.

This study addresses these questions by testing OSB and plywood in bending after subjecting them to various temperatures for different exposure times, hence characterizing the time dependence of strength as a function of temperature. More specifically, the objectives were to:

1. Study the effect of exposure time on bending strength, modulus of rupture (MOR) of OSB and plywood at elevated temperatures,
2. Interpret relationships between different temperature and time of exposure using a kinetics model for thermal degradation of strength, and
3. Develop a master curve representing temporal behavior of OSB and plywood at any reference temperature.

The master curve provides a predictive tool for residual strength and time to failure at a given reference temperature. By shifting the master curve reference temperature, it would be possible to predict residual strength following exposure at a wide range of temperatures for any amount of time.

Materials and methods

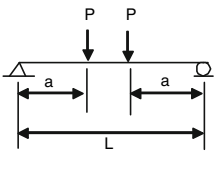
Commercially available aspen OSB and Douglas-fir plywood were selected for this study. The panels were rated C-D exposure 1, 32/16 span rated with thickness of 11.90 mm (15/32 in.) for plywood and 11.12 mm (7/16 in.) for OSB, respectively. The measured specific gravity of the phenol formaldehyde (PF) bonded plywood and OSB (PMDI in core; PF on the face) were 0.51 and 0.60, respectively.

Static third point bending tests were carried out to study the effect of temperature and exposure time on MOR of OSB and plywood. The bending specimens were cut along the major axis of each panel according to ASTM D 3043-00 (American Society for Testing and Materials 2006). The material was cut into specimens of size 406 $\times$ 76 mm^2 (16 $\times$ 3 in.). This study being a part of a larger project, half of each panel was used for bending samples (this study). The other half of the panel was reserved for future tests for properties like internal bond (IB), lateral nail connection strength and fracture toughness, which will be part of future publications. Therefore, for this study each panel yielded 45 bending samples. As much as 576 specimens each from OSB and plywood (1,152 in total) were prepared. The 576 OSB specimens were randomly divided into 72 exposure time–temperature groups with each group consisting of 8 specimens. The 72 groups allowed testing after exposure to 9 different temperatures (50, 75, 100, 125, 150, 175, 183, 191, and 200°C) and eight exposure time increments at each temperature ranging from 1 to

8 h at 1-h increments. Additionally, a set of control specimens were tested at room temperature. A similar randomized selection was done for plywood. For each temperature and each material a separate oven run was scheduled. As much as 64 samples for one temperature were placed in the oven, 8 samples were taken out of the oven every hour up to 8 h. The process was repeated for all the temperatures and both the materials. Once the specimens were taken out of the oven, they were allowed to cool to room temperature before testing.

All specimens were conditioned to equilibrium moisture content (EMC) prior to exposure to temperature. The measured EMCs were 6.7% for plywood and 4.9% for OSB. After exposure to elevated temperature, the specimens were cooled to room temperature for 24 h, but were not re-equilibrated with moisture. As a result, the strength changes of this study may represent the combined effects of strength changes due to moisture change and due to the prior high-temperature exposure. Separating these effects would require a control experiment determining strength as a function of moisture content below equilibrium moisture content in samples that were never exposed to high temperature. As the only way to reduce moisture content below equilibrium is to heat the specimens, such control experiments are not possible. Instead, it was assumed that slight increases in strength that might result from reduced moisture content were negligible compared to the observed decreases in strength due to high-temperature exposure. Justification of this assumption follows by noting that low-temperature results showed little or no increase in strength (where moisture effects might be expected to be more important and cause an increase) while high-temperature results showed significant strength reductions.

Third-point bending tests (Fig. 1) were conducted on an INSTRON 5582 machine. A constant span of 304.8 mm (12 in.) was used, which resulted in a span to depth ratio of 24 as recommended by ASTM D3043. The specimens were simply supported and loaded on the wide face by two equal, concentrated forces spaced equidistant between the supports. The specimens were loaded at a rate of 8 mm/min (0.314 in./min) and continued until failure. The modulus of rupture (MOR) and modulus of elasticity (MOE) were calculated by the equations in Fig. 1.



$$\Delta = \frac{Pa}{24EI}(3L^2 - 4a^2)$$

$$k = \frac{P}{\Delta}$$

$$E = \frac{ka}{24I}(3L^2 - 4a^2) \qquad MOR = \frac{2P_{max}L}{bd^2}$$

Fig. 1 All specimens were tested in third-point bending ($a = L/3$). Modulus (E or MOE) and strength (σ or MOR) were calculated from the above equations, where Δ = deflection at $L/2$, k = slope of load–deflection curve in the linear region, P = applied load, P_{max} = maximum load and I = bending moment of inertia

Results and discussion

Bending tests

The bending tests were conducted as function of exposure time and temperature. All lower temperatures (100°C and lower) showed little change in strength over 8 h; at higher temperatures (125°C and above), the strength decreased with time. As explained later in the "Modeling" section, all results were fit to straight lines based on an assumption of a constant, but temperature-dependent degradation rate for strength:

$$\frac{\mathrm{d}\sigma(t,T)}{\mathrm{d}T} = -\kappa(T) \quad \text{or} \quad \sigma(t,T) = \sigma(0) - \kappa(T)t \tag{1}$$

where σ is MOR, $k(T)$ is the temperature-dependent degradation rate (MPa/h) and $\sigma(0)$ is the MOR of control specimens. The straight line fits were constrained to go through the $\sigma(0)$ control value. The MORs after 8 h of exposure along with their respective weight losses are listed in Table 1 along with their R squared (R^2) values for the fit to Eq. (1). The 8-h strengths were calculated from the fit results rather than quoting the one result at 8 h, to provide a better representation of the complete set of data at each temperature. The R^2 values at higher temperatures (125°C and higher) suggest a good fit to the linear strength degradation assumption, however, the low R^2 values for lower temperature data are lower indicating a poor fit. These data hardly changed in strength and thus only scatter in the strength results remains and scatter was not related to exposure time. At 200°C, the linear fits predicted that plywood will have no residual strength after 8 h of exposure, while OSB will show a

Table 1 Predicted MOR values and weight loss values after 8 h of exposure for plywood and OSB at various temperatures with their root mean square error (R^2) values

Temperature (°C)	Plywood				OSB			
	$\sigma_{(0)} = 46.2$ MPa				$\sigma_{(0)} = 32.4$ MPa			
	σ_f (MPa)	% loss	R^2	Weight loss (%)	σ_f (MPa)	% loss	R^2	Weight loss (%)
50	46.8	−1	0.00	1.40	36.20	−12	0.20	0.57
75	39.4	15	0.38	3.26	29.34	9	0.02	2.73
100	33.9	27	0.23	5.17	33.47	−3	0.05	4.12
125	39.4	15	0.07	6.28	34.77	−7	0.00	4.13
150	38.6	17	0.20	6.46	29.73	8	0.01	4.96
175	27.2	41	0.21	7.13	27.93	14	0.33	5.56
183	26.7	42	0.50	8.83	17.41	46	0.82	6.81
191	13.6	71	0.78	9.61	17.22	47	0.87	7.48
200	0.0	100	0.65	NA	7.80	76	0.84	NA

$\sigma_{(0)}$ MOR of control specimens

σ_f Predicted MOR after 8 h of exposure

NA the samples caught fire prior to 8 h of exposure

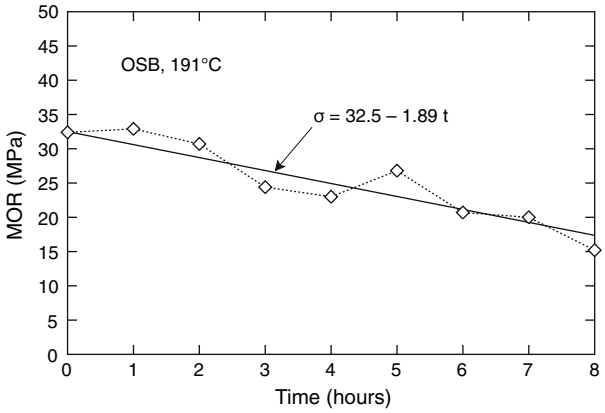


Fig. 2 MOR of OSB as a function of exposure time at 191°C. The linear fit assumes a constant degradation rate and was constrained to go through the control value at time zero

drop of 76% from its initial strength. At 191°C, decreases in strength of 70% and 47% are predicted after 8 h of exposure for plywood and OSB, respectively. This Fig. 2 shows one set of data for OSB at 191°C with its fit for degradation. Figure 3 shows MOR as a function of exposure time at all temperatures for plywood (Fig. 3a) and OSB (Fig. 3b), respectively. The results at high temperature (150°C and higher) clearly showed degradation; these experimental points are the filled symbols and their linear fits are the labeled, solid lines. The results at lower temperature (100°C and lower) had little or no degradation and their linear fits had small slopes, some of which were positive. This can also be observed from their respective R^2 values. Table 1 also shows that the bending strength slightly increased for plywood after 8 h of exposure to 50°C and also increased for OSB at 50, 100 and 125°C, respectively, but decreased at 75°C. These increases could be the result of two factors. First, all increases were within experimental scatter from the control values. In other words, there may be no increase. Second, at the lowest temperatures, the exposure may not cause any degradation of strength, but it might drive some moisture out of the specimen. Because moisture has an inverse relation with strength, if some moisture was removed, the low-temperature results could show an increase in strength. These experimental results are in open symbols in Fig. 3, and their fits are shown as the dashed lines. The results at 125°C were mixed. For plywood, degradation could be detected and is plotted in Fig. 3a as filled symbols and a solid line. For OSB, the constrained fit had a positive slope and is plotted in Fig. 3b as open symbols and a dashed line. By relaxing the constraint that the OSB results for 125°C must go through the control value, a degradation rate consistent with other results was determined; this adjusted rate was used in the modeling below.

Figure 3 shows that with an increase in exposure time at sufficient temperature, there is a decrease in bending strength for both materials. However, there was little or no consistent effect on bending strength after exposure to temperatures 100°C or less, even for 8 h of exposure. The strength loss results of this study hence can be

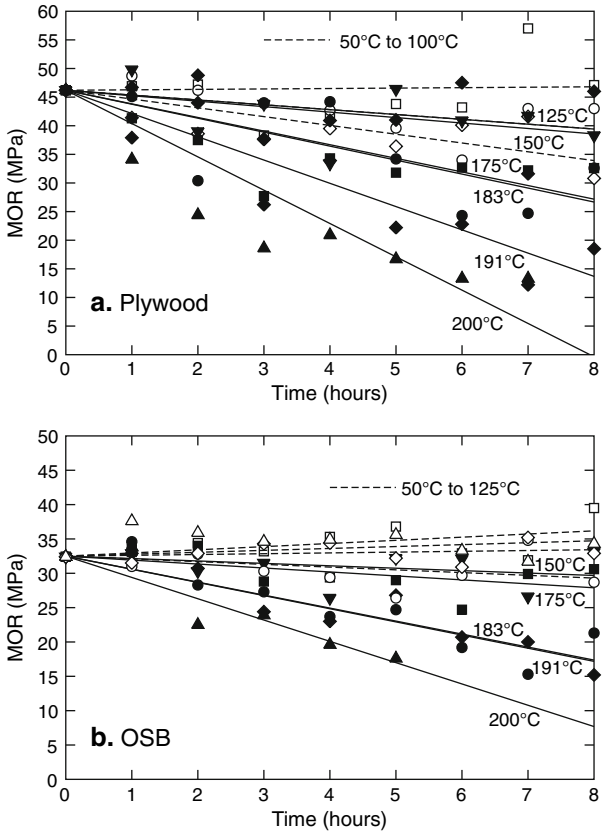


Fig. 3 Summary of all bending tests conducted as function of exposure time and temperatures for plywood (**a**) and for OSB (**b**). The experimental results are the symbols; the *straight lines* are fits assuming a constant degradation rate

described using two regimes. The first regime is where the temperature of exposure is less than or equal to 100°C, and the second is where the exposure temperature is 125°C and higher. There is evidence in the literature (Green et al. 1999) that wood does not deteriorate at sustained exposure to 100°C. Plywood and OSB, however, are composites that contain wood and resin as adhesive. Even if the wood does not deteriorate at 100°C, the resins used in OSB and plywood might deteriorate which would in turn cause degradation in strength of the composite. A 15% reduction in strength of OSB was observed by Bekhta et al. (2003) at 100°C while a 30% loss in strength was observed at 140°C, each after exposure of 1 h at that temperature followed by testing at that same elevated temperature. As their tests were conducted at the exposure temperature rather than after cooling down to room temperature, there is bound to be some difference in results compared to the present study. Winandy et al. (1988; 1991) did observe room-temperature strength loss in plywood exposed to temperatures below 100°C, but the degradation took much longer than 8 h. Apparently, degradation does occur below 100°C, but the amount of

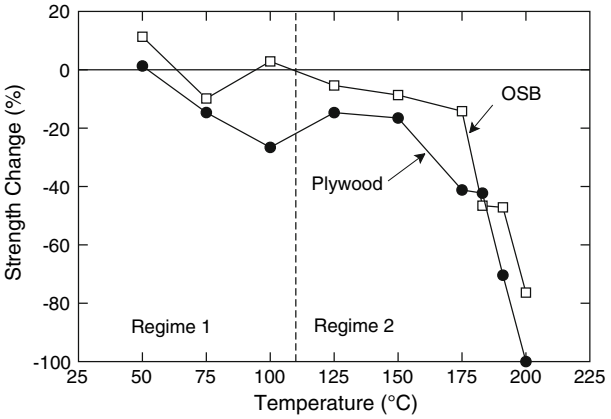


Fig. 4 The calculated strength loss after 8 h of exposure as a function of exposure temperature for plywood (*filled symbols*) and OSB (*open symbols*)

degradation compared to scatter or compared to moisture-change effects was too small to detect in 8-h tests used by the authors.

The second regime occurs at 100°C and higher, where the degradation in strength of the composite is the combined effect of degradation of the wood and degradation of the resin. As seen in Fig. 3, there is a decrease in MOR at every temperature above 100°C for both OSB and plywood. Figure 4 summarizes the results by plotting the strength loss from the curve fits after 8 h of exposure as a function of temperature. At 200°C, the samples were not able to sustain the heat exposure and caught fire at 7 and 5 h of exposure for plywood and OSB, respectively. Plywood lost 71% of its initial strength after 7 h of exposure at 200°C, while OSB lost 47% after 5 h of exposure at the same temperature. Figure 4 plots the strength loss after 8 h by extrapolating the degradation rate from the first 7 or 5 h of results. The 125°C results for OSB used an unconstrained fit rather than the fit given in Fig. 3. The dashed vertical line divides the results into regime 1 for 100°C and lower and regime 2 for 125°C and higher. The data in regime 2 were used for the modeling in the next section.

Degradation kinetics modeling

The measured strengths were used to model thermal degradation as a function of temperature and exposure time. Strength of solid wood has two-stages of degradation. Below 200°C there is a slow decline in strength, but as temperature increases beyond 200°C, a rapid decrease in strength is observed (Schaffer 1970) due to degradation of hemicelluloses at 200°C (Beall and Eickner 1970). Strength loss can be predicted from exposure time at elevated temperature, based on kinetics modeling (Mitchell et al. 1953; Winandy and Lebow 1996; Gao et al. 2006). Similarly, the strength data here were evaluated using kinetics methods. Since all results were below 200°C, a single-degradation process was assumed. Stamm (1964) also supports this approach.

The thermal degradation model assumed that the strength degradation follows the constant degradation rate in Eq. (1). Modeling of such first-order kinetics requires an equation for the temperature dependence of the rate constant (Winandy et al. 1991). For cellulosic materials, this rate constant can represent rate of change in concentration of a chemical constituent. For mechanical properties, it can be rate of change in any measured property, such as strength (Millett and Gerhards 1972). Here, the temperature dependence was assumed to follow an Arrhenius activation energy equation:

$$\kappa(T) = Ae^{-E_a/(RT)} \tag{2}$$

where A is constant, E_a is activation energy, R is the gas constant and T is the absolute temperature (K).

For all exposure temperatures, $k(T)$, was found from the slopes of the linear fits in Fig. 3 (for OSB at 125°C, $k(T)$ was found for a fit that was not constrained to go through the control value). Next, the model parameters ($k(T)$) for each temperature were fit to the Arrhenius activation energy theory model. The Arrhenius activation energy model can be represented in logarithmic form as follows:

$$\ln \kappa(T) = \ln A - \frac{E_a}{RT}. \tag{3}$$

Figure 5 plots ln $k(T)$ for temperatures above 100°C and for both plywood and OSB. The straight lines are the fits to Arrhenius equation in Eq. (3). For plywood, the 77°C degradation rate from Winandy et al. (1991) was included in the fitting process. The rate constants for both plywood and OSB closely followed the Arrhenius equation. Furthermore, extrapolation of the high-temperature results of this study to low temperature was consistent with the one low-temperature result from Winandy et al. (1991). From the slopes, the apparent activation energies were 54 and 65 kJ/mol for OSB and plywood, respectively. These values are lower than

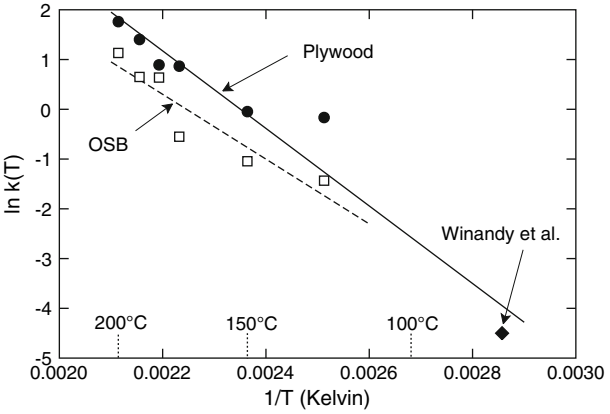


Fig. 5 Arrhenius activation energy plot for ln $k(T)$ as a function of 1/T for plywood (*filled symbols*) and OSB (*open symbols*) including only results above 100°C. The "Winandy et al." result at 77°C for plywood is plotted as the *filled diamond*

that of solid wood, which has activation energy for degradation below 200°C of 74–107 kJ/mol (Gao et al. 2006). Winandy and Lebow (1996) calculated an activation energy of 93 kJ/mol required for thermal degradation of wood below 200°C. This value falls within the range of values calculated by Gao et al. (2006). The authors are not aware of a similar study on plywood or OSB for comparison to these new results.

The quality of the fits and the consistency with the Winandy et al. (1991) results suggest that a single Arrhenius activation energy can model degradation of wood composites from low temperature up to 200°C. The experiments of this study could measure $k(T)$ for 125°C and above. For 100°C and lower, however, there was too much scatter in strength experiments to detect the small amount of degradation that would occur in 8 h. Even at 125°C, the measured rates deviated to faster degradation than expected (i.e., above the fits), suggesting that the short-term 125°C results may be unreliable. All results 150°C and higher, however, were consistent. Measuring $k(T)$ at 125°C and lower, requires long-term experiments. An alternative to long-term tests is to find degradation rates by extrapolation of short-term, high-temperature results using the Arrhenius equation. This approach is described in "Master curve analysis" section to construct master curves for degradation of plywood and OSB over a wide range of reference temperatures.

Master curve analysis

Time–temperature superposition (TTSP) is a common extrapolation technique for experiments involving both temperature and time. It is most frequently used for studying viscoelastic properties of polymers (Aklonis and MacKnight 1983), but it can have application in other properties as well. Here, it will be used to study degradation in strength. The principle of TTSP is that a property measured over a short time at a higher temperature is equivalent to that property measured over a long time at a lower temperature (Aklonis and MacKnight 1983). The superposition is guided by the kinetics of the underlying mechanisms of the studied process. Here, the kinetics described by the Arrhenius equation guides the superposition. First, short-term experimental data for successively increasing temperature levels (accelerated data) are plotted against log-time. Next, a reference temperature is chosen and data at other temperatures are shifted until they overlap the results at the reference temperature. Experimental curves at temperatures above the reference temperature are shifted right, and those below the reference temperature are shifted left along a log-time axis. The resulting master curve predicts the behavior of the measured property at the reference temperature over a much wider timescale. An experimental output of TTSP is the temperature dependence of the shift factor, a_T, defined by

$$\log t_{\text{ref}} = \log t(T) - \log a_T \tag{4}$$

In other words, the effective time at the reference temperature, t_{ref}, is shifted along a log-scale from the measured time at the test temperature, $t(T)$. The shift factor, log a_T, is negative for temperatures below the reference temperature and positive for temperatures above the reference temperature.

The above shifting process requires data with sufficient changes over the timescale of the experiments to detect overlap and usually requires relatively low scatter. These criteria are commonly met by visco-elasticity data of polymers, but are not met by the strength data of this study. If the kinetics of the underlying process is known, however, that kinetics analysis, rather than experimental data overlap, can be used to construct the master plot. Using the assumption of the authors of a linear decay rate, the condition to obtain equivalent strength loss at two different temperatures is when

$$k(T_{\text{ref}})t_{\text{ref}} = k(T)t(T) \tag{5}$$

Comparing to Eq. (4), the experimental shift factor from temperature T to any reference temperature can be found from

$$\log a_T = \log\left(\frac{k(T_{\text{ref}})}{k(T)}\right) \tag{6}$$

This shift factor can be determined directly from linear fits to degradation experiments without any kinetics modeling (i.e., directly from $k(T)$ without any use of Arrhenius activation energy fits). If the kinetic modeling is used to express $k(T)$, however, it is possible to calculate the expected shift factor from the measured activation energy:

$$\log a_T = \frac{E_a}{R\ln 10}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right) \tag{7}$$

Shift factors for a reference temperature of $T_{\text{ref}} = 150°\text{C}$ were calculated from experimental results for $k(T)$ above 100°C and are plotted in Fig. 6 for plywood (Fig. 6a) and OSB (Fig. 6b), respectively. These results are plotted as solid symbols. For results 100°C and lower, the results are plotted in Fig. 6 as open symbols. The only low-temperature results that could be plotted, however, were the ones that had positive $k(T)$. Finally, the shift factor for plywood from the results of Winandy et al. (1991) for an exposure time of 63 days at 77°C for N grade Southern pine plywood 15.9 mm (0.625 in) in thickness is plotted in Fig. 6a. The smooth curves plotted in Fig. 6 are the predicted shift factors from the Arrhenius equation (Eq. 7) found using the activation energies determined in the kinetics modeling section. For both plywood and OSB, the Arrhenius shift factor agreed well for results 150°C and higher. At 125°C, the experimental shift factors deviated below the curves. For results 100°C and below, the data of this study could not determine $k(T)$ and thus could not determine a shift factor. The theoretical curve increases rapidly at lower temperatures. Because it is close to the Winandy et al. (1991) results, it was claimed that the Arrhenius rate constant accurately represents the degradation of plywood from 200°C down to at least 77°C. Winandy et al. (1991) also studied the degradation of strength at 66°C for 63 days, but the strength increased, hence providing a negative rate for degradation of strength. This result indicates that while an Arrhenius extrapolation down 77°C seems reasonable, there are no experimental results confirming that the extrapolation can continue to even lower temperatures. Similarly for OSB, only experimental data above 100°C were

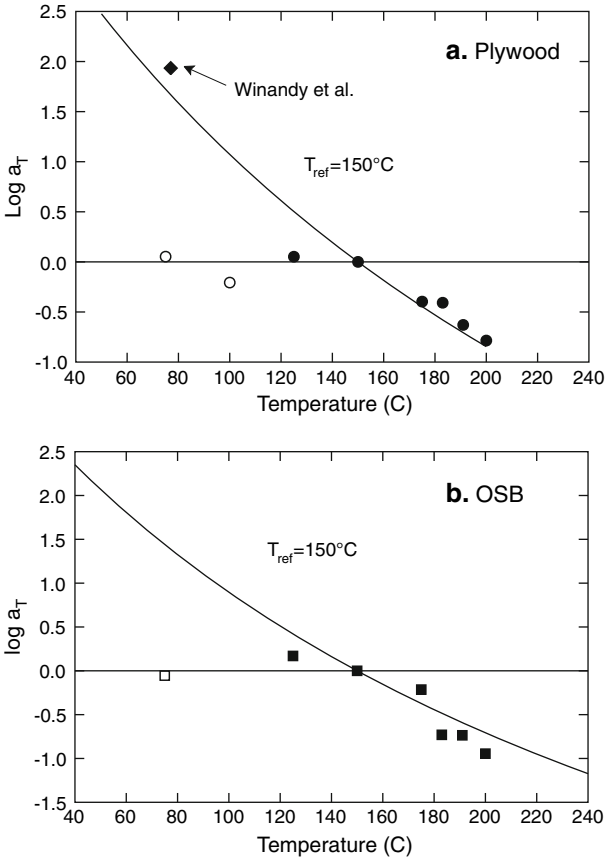


Fig. 6 Shift factors, log a_T, calculated from experiment results for $k(T)$ (symbols, Eq. 6) and by Arrhenius activation energy (curves, Eq. 7) for **a** plywood and **b** OSB

used to obtain the shift factors, as they showed degradation in strength over time when exposed to elevated temperature. At or below 100°C, degradation was in regime 1 and too small to detect in the 8-h time frame of the experiments. One experimental result decreased in strength, and the result is plotted as an open symbol. The curve is prediction of the shift factor from the Arrhenius equation (see Eq. 7) using the activation energy determined in the kinetics modeling.

Next, the shift factors were used to transform experimental data into master degradation plots at a reference temperature of 150°C. The master curves are shown in Figs. 7 and 8 for plywood and OSB, respectively. The curves indicate that TTSP can be used to develop long-term thermal strength degradation curves. Such master curves convert a series of short-term tests into a prediction of long-term behavior at the reference temperature. The 150°C curve now spans four decades in time while the input data was only one decade. Experimental data points in the master curve from different temperatures are represented by different symbols. The initial horizontal portion of the curve refers to the data obtained after exposure to

temperatures below 100°C; these data were shifted using theoretical shift factors and are represented by open symbols. In contrast, the experimental results 125°C and above were shifted according to actual shift factors (from Eq. 6) and are represented by filled symbols. The shift factors and methods used for generating the master curves are tabulated in Table 2. The smooth curve through the points was a least-square cubic spline smoothing of the experimental data.

Figures 7 and 8 plot the master curve for degradation of strength on exposure to 150°C over time on a log-scale for plywood and OSB, respectively. Although, the initial strength of plywood is higher than that of OSB, plywood degrades faster than OSB. The strength of plywood at 150°C decreases by around 70% in approximately 19 h, while it takes 100 h for the strength of OSB to drop to 59%. Another contrasting aspect in the behavior of OSB and plywood at 150°C is that the strength of OSB does not vary much for the first 10 h, after which the strength starts to degrade. However, for plywood the strength remains constant for only about 1 h of exposure before starting to degrade. As plywood has a layered structure, the strength of the plywood is highly dependent on glue between the layers. OSB, on the other hand is comprised of densely packed flakes and glue is applied as droplets. The structure of OSB is such that it distributes defects more efficiently. If the glue starts to deteriorate, one might expect plywood to deteriorate faster since it is more dependent on the integrity of its fewer glue bonds. One interpretation of the authors' results is that plywood has higher room-temperature strength because of its more regular structure, more highly aligned plies, and efficient load transfer between plies through the resin. But, when exposed to elevated temperature, the degradation of the integral glue lines causes more rapid degradation in strength. In contrast, OSB distributes resin throughout the composite. The less-oriented structure and perhaps less-efficient glue bonds result in lower room-temperature strength, but when exposed to elevated temperature, the strength is less sensitive to early stages of glue degradation. In brief, the elevated temperature strength performance of OSB is better than that of plywood.

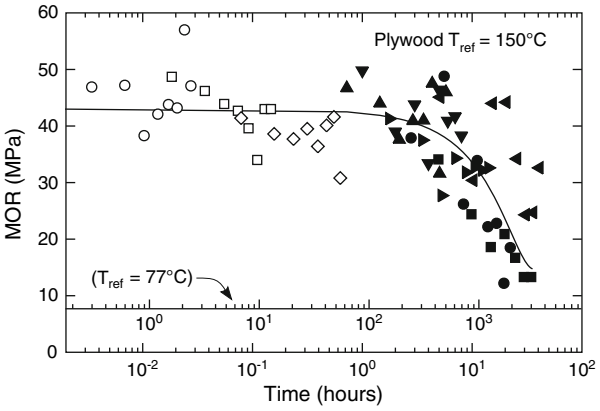


Fig. 7 Master curve for degradation in strength (MOR) of plywood. The main axis references a reference temperature of 150°C. The inset *x*-axis is the time axis for a reference temperature of 77°C

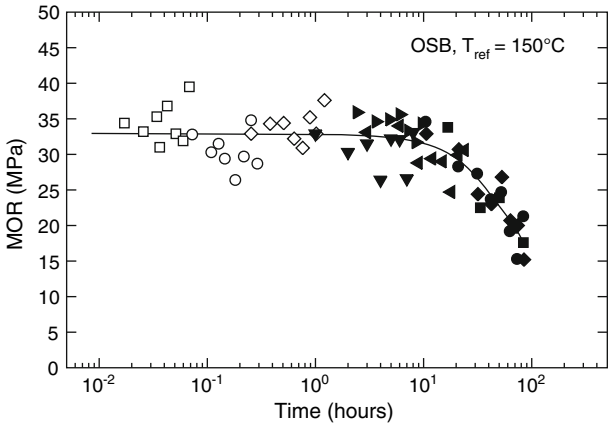


Fig. 8 Master curve for degradation in strength (MOR) of OSB. The main axis references a reference temperature of 150°C

Table 2 Log at values used to produce the master curve for plywood and OSB for a reference temperature of 150°C

Temperature (°C)	Log (a_t)		Method
	Plywood	OSB	
50	1.658	2.069	Arrhenius
75	1.154	1.440	Arrhenius
100	0.718	0.896	Arrhenius
125	0.142	0.169	Actual k
150	0.000	0.000	Actual k
175	−0.246	−0.222	Actual k
183	−0.444	−0.765	Actual k
191	−0.693	−0.773	Actual k
200	−0.710	−0.971	Actual k

Master curves provide predictive estimates of failure time and residual strength of a material for prolonged exposure at the reference temperature. Considering the 150°C master plot for plywood (Fig. 7), the smoothed curve predicts a residual strength after 10 h of exposure to be 36 MPa. Similarly, the residual strength can be obtained from the master plot for any given exposure time. By defining failure at a certain percentage of initial strength, one can predict the time to failure at 150°C. For example, if failure is defined as 50% strength loss, then the failure time at 150°C is approximately 12 h. Similarly, analyses could be done for OSB at the reference temperature of 150°C (Fig. 8). Compared to plywood, the 50% strength reduction time for OSB is approximately 90 hat 150°C.

Time–temperature superposition can be carried out for any reference temperature. The generic shape of the curve remains the same for each reference temperature, only the timescale changes or shifts as the reference temperature changes. The shift to any new reference temperature can be determined from

experimental shift factors. As an example, a master plot for plywood at a reference temperature of 77°C was generated using the plywood shift factors and the scale is shown as an inset in Fig. 7. First, Eq. (2) was used to calculate $k(T_{ref})$. Next the experimental results below 100°C were shifted by again finding $k(T)$ by Arrhenius activation energy and shifted according to Eq. (6). The results here above 100°C were shifted using measured $k(T)$ and Eq. (6). As expected, the shape of the curve is the same while only the timescale has shifted. This new master plot predicts a 16% loss in strength in approximately 41 days, which is similar to the observed 16% loss in strength in 63 days (Winandy et al. 1991). This result further suggests that an Arrhenius rate constant accurately represents the degradation of plywood from 200°C down to at least 77°C.

Post-fire residual strength of structural composites that were not affected by direct fire, but were exposed to elevated temperature is a critical piece of information. Knowledge of response to high-temperature exposure can lead to more informed decisions on whether a structure needs to be deconstructed completely or just partly. For modest exposure temperatures (<100°C), long-term tests would be required if those tests had to be carried out at the exposure temperature. An alternative to long-term tests is to obtain degradation rates from several short-term experiments at several higher temperatures. The results in this section show that such short-term test can be shifted by experiment results or by analysis with simple Arrhenius activation energy theory to construct a master plot. The master plot provides an accelerated test method for long-term results. By shifting the master plot to any exposure temperature of interest, the resulting strength of plywood or OSB can be predicted. All results here used strengths determined from small specimens cut from the panel. Since the accelerated methods can obtain results in shorter tests, one recommendation of this study is to repeat the higher-temperature results for full-scale panels.

Conclusion

Strength (MOR) of both OSB and plywood decreased as a function of temperature and exposure time. The degradation results were divided into two regimes. The rate of change of strength was greater at higher temperature than at lower temperature. A kinetics analysis and Arrhenius activation energy theory of the strength degradation data was valid for temperatures above 100°C. The degradation rate $k(T)$ follows the relation $k(T) = 40E6e^{-7549/T}$ for plywood and $k(T) = 2E6e^{-6510/T}$ for OSB. The apparent activation energies were 54.1 kJ/mol for OSB and 62.8 kJ/mol for plywood. Using the kinetics analysis along with time–temperature superposition, a master curve was generated at a reference temperature of 150°C. The master curve can be used for residual strength estimates and failure time predictions. The master curves show that although plywood has a higher initial strength, OSB performs better in terms of strength degradation after exposure to elevated temperature. After longer-term exposures, the strength of OSB is higher than plywood.

Acknowledgments The author would like to acknowledge the support of the Wood based Composite Center for funding the project.

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