DEGRADATION OF YIELD STRENGTH OF LATERALLY LOADED WOOD-TO-ORIENTED STRANDBOARD CONNECTIONS AFTER EXPOSURE TO ELEVATED TEMPERATURES

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Abstract. Wood-to-sheathing connections are crucial to the lateral force resisting system of a wood-frame structure. Engineers are often faced with the challenge of predicting strength of a partially damaged structure after it has been exposed to elevated temperature during a fire. Numerical simulations to predict the residual strength need thermal degradation data and models for the material as well as the connections. Therefore, it is important to categorize connection response when exposed to elevated temperatures for a sustained period of time. This study addresses this issue by developing models to predict lateral yield strength degradation of wood-to-oriented strandboard (OSB) connections after exposure to elevated temperature. A total of 394 Douglas-fir-to-OSB connections were tested laterally as a function of eight different temperatures and eight exposure times within each temperature regime. Yield strength of the connection decreased as a function of temperature and exposure time. Rate of degradation was greater at higher temperatures. A regression-based statistical model was developed. Additionally, these results were fit to a two-step simple kinetics model, based on the assumption of degradation kinetics following an Arrhenius activation energy model. The kinetics-based model was preferred to the regression model because it fit the data better with one less parameter and predictions consistently matched the observed values for an independent data set.

Keywords: Arrhenius activation energy, Douglas-fir, kinetics model, regression.

INTRODUCTION

Wood is a predominant building material in the United States, especially in the residential construction sector. In a wood-frame structure, shear walls, interior and partition walls, roofs, and floors are fabricated with solid-sawn lumber as the framing material and sheathed with a panel product. Since its inception, oriented strandboard (OSB) connected to the framing using a dowel-type fastener has been a predominant sheathing material in a wood-frame shear wall. Performance of a wooden shear wall in light-frame construction is highly dependent on connections. Connection performance has been the subject of many experimental studies (Foschi 1974; McLain 1975; Foschi and Bonac 1977; Price and Gromala 1980; Aune and Patton-Mallory 1986a; Theilen et al 1998; Kent et al 2004; Sinha et al 2011a; Sinha and Avila 2014) and numerical modeling (Kuenzi 1955; Aune and Patton-Mallory 1986b; Pellicane 1991; Smith et al 2001; Nishiyama and Ando 2003).

A majority of the studies were performed to obtain ambient temperature performance. Not many studies have characterized the performance of connections at or after exposure to elevated temperature. It is well documented that exposure

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to elevated temperatures causes a change in mechanical properties of wood (Winandy and Lebow 1996; Buchanan 2002; AFPA 2005; FPL 2010; Sinha 2013) and wood-based composites (Winandy et al 1988, 1991; Sinha et al 2011b, 2011c). Exposure to elevated temperature may also have an effect on the strength of laterally loaded nail connections because the dowel-bearing capacity is decreased as a result of thermal degradation. As a result, the National Design Specification (NDS) uses a temperature factor, C_t, to decrease design values when the member or the connection is subjected to elevated temperature for a sustained period of time (ANSI/AWC 2015). Sinha et al (2011a) characterized performance of wood-to-OSB construction after exposure to elevated temperatures. Two temperatures were considered (100°C and 200°C) with two different exposure times (1 and 2 h). A significant decrease in wood-to-OSB connection yield strength was observed at 200°C with 2 h of exposure time.

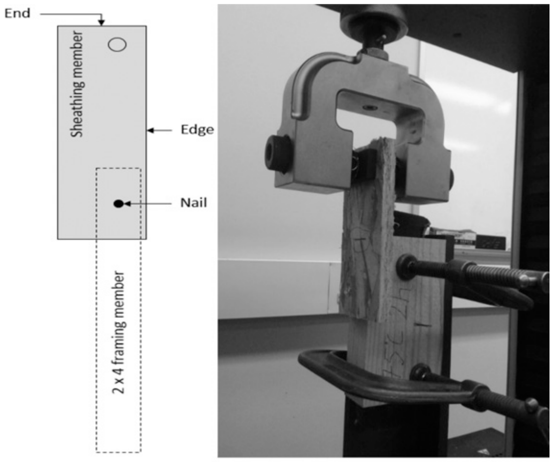
Noren (1996) tested wood-to-wood nailed joints for endurance under fire exposure to determine failure load and time to failure under fire. Sinha et al (2011c) characterized the performance of wood-to-OSB construction after exposure to elevated temperatures. Two temperatures were considered (100°C and 200°C) with two different exposure times (1 and 2 h). A significant decrease in wood-to-OSB connection was observed at 200°C with 2 h of exposure time. Sinha et al (2011a) further demonstrated that NDS yield models could predict the degradation in yield strength of the connection by accounting for the degradation in dowel-bearing strength of the members. Similar to Noren (1996), the predicted mode of failure consistently matched the observed mode of failure of the joints. Earlier work on elevated temperature properties of a connection focused on wood-to-gypsum connections (Fuller 1990) and metal plate connectors (Shrestha et al 1995). Peyer and Cramer (1999) tested plywood-to-wood joints at elevated temperatures (30°C, 120°C, 200°C, and 265°C) and concluded that elevated temperatures decreased the strength and connection stiffness even at low temperature (120°C). The greatest percentage decrease in strength (13%) and connection stiffness (47%) occurred between ambient temperature (30°C) and 120°C. Peyer and Cramer (1999) predicted the failure of assemblies at elevated temperature.

Fire-resistant design has a 2-fold objective. One is to ensure structural integrity during fire to allow the inhabitants ample time to evacuate. The second is to design rehabilitation and retrofit plans for fire-damaged partially burnt structures. To that end, knowledge of residual strength of materials and connections is required for performance simulations to be conducted to design and verify the rehabilitation plan. In a typical wood-frame shear wall, dimension lumber is used as framing, which is anchored to the foundation and connected to engineered wood panel sheathing such as OSB with dowel-type fasteners. To build robust simulations, degradation information is needed on all aspects of a wall system—the framing material, sheathing, and their connections.

The objective of this study was to characterize the degradation in lateral load carrying capacity of a wood-to-OSB nail connection as a function of exposure temperature and times. Also, models are proposed to predict the residual load carrying capacity of the connections.

MATERIALS AND METHODS

Standard wood-frame construction has two different sheathing-to-framing nail joint configurations. They are edge connection (nail positioned 19 mm from the panel edge, loaded parallel to the fiber direction of the main member) and plate connection (nail positioned 19 mm from the panel end, loaded perpendicular to fiber direction of the main member). The predominant difference is that the direction of loading with respect to the framing member is parallel to the grain direction in the panel edge connection, whereas it is perpendicular to the grain in the panel plate connection. In this study, only panel edge geometry as shown in Figure 1a was tested because, as per the NDS, connections using dowels less than 6.35 mm in diameter are independent of the grain direction (ANSI/AWC 2015).



(a) (b)

Figure 1. Connection geometry schematic (a) and test set-up (b).

The connection samples were constructed with 38- × 89-mm Douglas-fir (*Pseudotsuga menziesii*) No. 2 or better as the framing member and 11.9-mm-thick OSB as the sheathing material. The specific gravity of Douglas-fir and OSB were 0.46 and 0.59, respectively. A single-shear nail connection was constructed using smooth-shank nails (3.8 mm diameter, 75 mm length, $f_{\mathrm{by}} =$ 620 MPa). The bending yield strength of the nail was evaluated by the manufacturer using ASTM (2007). The nails were driven using a nail gun such that the nail head stuck out a few millimeters from the surface of the OSB. The connections were finished manually with a hammer. The nails were centered in the thickness of the framing member. The sides of the framing and sheathing material were flush, meaning neither specimen extended out more than the other. After the connections were constructed, the test samples were stored in an ASTM standard conditioning room that was maintained at 65% RH and 20°C until the time of exposure to elevated temperature.

A total of 394 connections were fabricated. These samples were then randomly subdivided into 64 exposure groups with each consisting of six specimens. The remaining 10 specimens were designated as controls. The 64 exposure groups allowed for testing after exposure to eight different temperatures (75°C, 100°C, 120°C, 140°C, 160°C, 180°C, 190°C, and 200°C) and eight exposure times at each temperature ranging from 1 to 8 h at 1-h increments. Several studies (Fuller 1990; Young and Clancy 2001; Frangi et al 2010) characterized the temperature distribution for unexposed and protected wall assemblies. These studies suggested that with varying thickness of gypsum wall board, the temperature exposed varies. Studies concurred that 100°C was a common temperature for 60-90 min of exposure. Although in severe cases of fire, the temperature can rise to 200°C. Therefore, this study characterized a temperature regime to 200°C.

For each temperature, a separate oven run was scheduled. Sixty-four samples for one temperature were placed in the oven. Six samples were taken out of the oven every hour until 8 h. The process was repeated for all the temperatures. After the specimens were taken out of the oven, they were allowed to cool to room temperature before testing. The test program was designed to specifically measure the ambient temperature properties after exposure to elevated temperatures, thereby characterizing residual strength of the connection at room temperature.

The edge test had the specimen structures clamped to a perpendicular metal bracket (Fig 1b). Care was taken in setting up the apparatus to minimize all eccentricities in loading caused by nail withdrawal. The universal testing machine (Instron 5582; Instron, Norwood, MA) used had a steady displacement rate of 5 mm/min.

Load-deflection curves (P-Δ) were recorded for each test. The test was stopped after the P-Δ curve leveled off. Yield strength was calculated from the load and deflection curves using a 5% diameter offset. Yield strength was defined by the 5% offset method as the intersection of the load-deformation (P-Δ) curve and a line parallel to the initial linear portion of the P-Δ curve offset by 0.05 times the shank diameter of the nail in the positive direction. Here, the offset was rounded to 0.19 mm. After testing each specimen, the nails were taken out of the wood and their model of yielding was determined as per the NDS (ANSI/AWC 2015).

RESULTS AND DISCUSSION

The lateral nail connection tests were conducted as a function of temperature (T) and exposure time (t). Yield load (P_y) was calculated using the 5% offset method, and its dependence on temperature and exposure time is given in Figure 2. The results were fitted to straight line fits based on an assumption of a constant temperature-dependent rate of degradation of P_y, which is represented as

$$\frac{\mathrm{d}P_y(t,T)}{\mathrm{d}T} = -k(T) \text{ or}$$

$$P_y(t,T) = \sigma(0) - k(T)t \qquad (1)$$

Summary of the test results after each exposure temperature and 8 h of exposure time is given in Table 1. Along with mean P_y, the coefficient of variation (COV) and degradation constant at each temperature and the R^2 values to the linear fits are also given in Table 1. As exposure times increased in each temperature regime, a decrease in P_y was observed (Fig 2). The percentage yield strength drop also increased with increase in temperature at 8 h of exposure (Table 1). There was a 25.6% yield strength drop observed at 200°C after 8 h of exposure. As expected, at higher temperatures, variability in the data increased with COV at 190°C and 200°C being 12.9% and 15.2%, respectively.

Linear fits to the data as per Eq 1 are given in Figure 2. The fits were constrained to pass through the initial P_y values (controls). The corresponding degradation rate k and R^2 values for each temperature are listed in Table 1. The degradation rate increased as temperature increased. For 75°C and 200°C, the R^2 values, which are a measure of the goodness of a linear fit, were negative. For other temperatures in between, positive R^2 values were observed and ranged

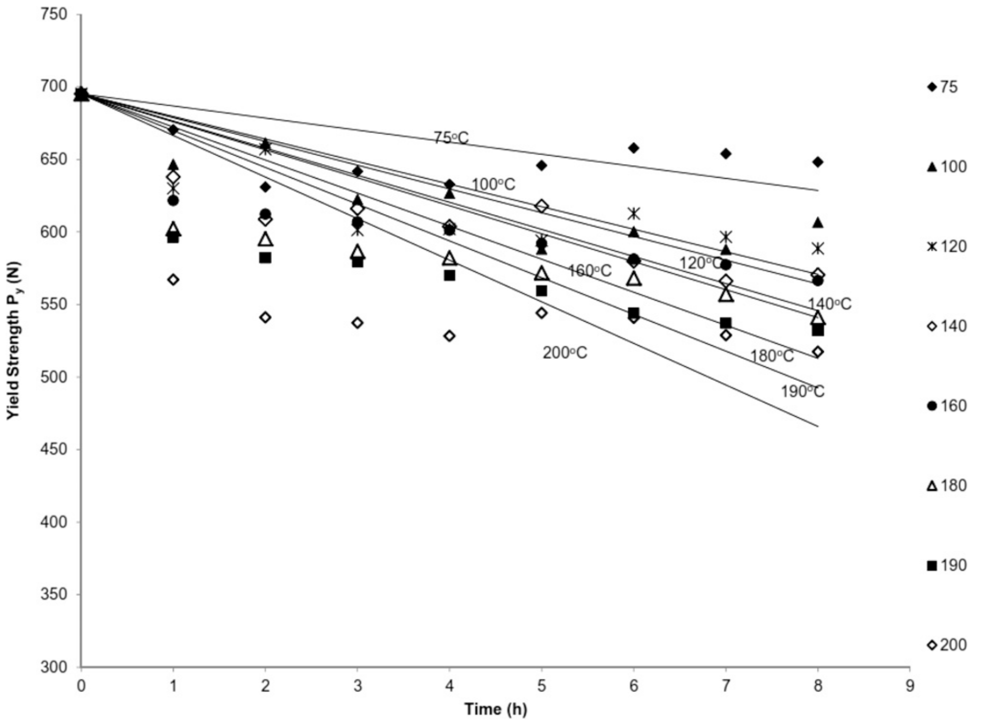


Figure 2. Yield strength of laterally loaded wood-to-OSB connections as a function of time and temperature.

Table 1. Summary of connection tests after 8 h of exposure along with their COV, slope, and R^2 values for straight line fits with and without the constraints of passing through the initial value. Also listed are initial yield strengths and their COV.

T (°C)	P_y init P_y (N)	695 N (12%) COV (%)	% Drop	With intercept constraints k	R^2	Without intercept constraint k	R^2
75	648	10.3	6.8	8.33	−0.58	2.99	0.16
100	607	9.2	12.8	15.56	0.61	11.46	0.75
120	589	19.3	15.3	16.37	0.33	10.37	0.64
140	570	11.4	17.9	18.69	0.56	12.84	0.78
160	567	11.5	18.5	19.28	0.38	12.08	0.76
180	541	12.3	22.2	22.79	0.27	12.01	0.74
190	532	12.9	23.4	23.08	0.31	12.47	0.72
200	517	15.2	25.6	28.66	−0.03	13.67	0.47

from 0.27 to 0.61, suggesting a satisfactory fit. This poses a question regarding justification of linear fit to the data. This low and negative R^2 was an artifact of containing the fit through the initial values. Our initial value for yield strength was significantly greater than that of the 1-h exposure values for all temperatures except 75°C. This is unusual because at 1-h exposure at a high temperature, moisture is driven out of the wood resulting in increased strength of wood and wood composites. Our observation of high control values perhaps was a result of natural variation of the material at hand. To justify our linear fits to the data, the constraint of passing through the initial value was removed. The corresponding degradation constant and R^2 values are also given in Table 1. With the constraint removed, there was a decrease in the rate of degradation (k) compared with the k values with the constraints. The R^2 values significantly improved with all values being positive and were in excess of 0.64 except for 75°C and 200°C. Expectedly, there was hardly any degradation at 75°C. Therefore, a low R^2 of 0.16 was observed. At 200°C, a R^2 of 0.47 was observed, which is not as good a fit as other temperatures but is acceptable. The R^2 values thus obtained without the constraint of passing through the initial values justify the linear fit to the data. However, for the kinetics model as presented in the next section, the k values obtained using the constraint will be used because the controls served as a benchmark with which the strength drops were calculated and compared against.

NDS specifies six yield modes by which a connection can yield. The mode of yielding for all time and temperature combinations was III_s. Mode III_s refers to a yield mode in which crushing of the wood occurs in the side member (or sheathing) and bending of the nail occurs just beneath the surface of the main member. When the nail is extracted, a distinct plastic hinge is observed. Sinha et al (2011a) also observed III_s yield mode with occasional mode II yielding at higher temperatures. After exposure to elevated temperature and because of degradation in embedment strength of OSB as reported by Sinha et al (2011a), mode II yielding of connections was expected as opposed to mode III_s. This was, however, not observed in this study. Some examples of mode III yielded nails are shown in Figure 3.

Regression

Yield strength of a connection varied with exposure time (t) and temperature (T). The effect of these variables and their interactions on the yield strength was investigated first using analysis of variance (ANOVA). Subsequently, the relationship of the main effects t and T and their interaction with yield strength was defined using a multiple linear regression model constructed using individual data points. The model follows the form of

$$P_y = \beta_0 + \beta_1 t + \beta_2 T + \beta_3 t T \qquad (2)$$

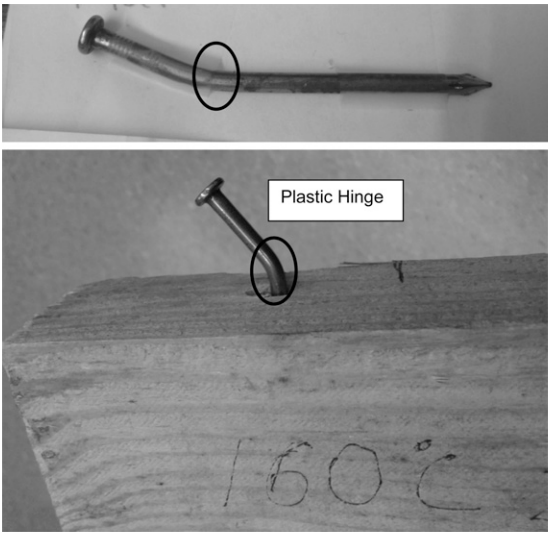


Figure 3. Two examples of mode III yielding.

where β_i are the regression coefficients associated with various terms, T is the temperature (celsius), and t is the time of exposure (hours). ANOVA results suggest both time ($p < 0.001$) and temperature ($p \ll 0.001$) affect yield strength significantly, whereas the interaction between time and temperature was not significant ($p > 0.05$). However, our results indicate that yield strength decreased as exposure time increased at a given temperature. The rate of degradation was temperature dependent as shown in Figure 2 in which yield strength decreased at a different rate for each exposure temperature. This was verified by the kinetics model. Therefore, it became important to include an interaction between time and temperature in the model regardless of its statistical significance.

The linear regression model for P_y is as follows:

$$P_y(N) = 712.28 + 3.3435t - 0.6368T - 0.0168Tt \;\; (F = 30.98;\ p < 0.0001) \tag{3}$$

The F and p statistics are a measure of how well the model represents the data set. p value less than 0.0001 suggests that the dependence of P_y on temperature and exposure time was highly significant and represented the data set very well. Previously, Sinha et al (2011a) reported the degradation of yield strength with exposure to elevated temperature but did not present a model. Also, that study only included four time-temperature combinations in addition to the controls as opposed to 64 combinations in this study.

Kinetics Model

Yield strength was used to model thermal degradation of connections as a function of temperature and exposure time using kinetics principles. Kinetics-based degradation models are based on the assumption that degradation kinetics follows an Arrhenius activation energy model. This assumption has two components. First, at a constant temperature (T), the rate of change of yield strength is dependent on the time of exposure (t) as depicted in Eq 1. This part is similar to linear regression, in which at constant temperature (T), the yield strength degrades linearly with time of exposure (t). This is true for the test results as shown in Figure 2 and Table 1. Subsequently, at a given time, the change in property follows an activation energy theory assumption which can be represented as

$$k(T) = Ae^{-E_a/(RT)} \tag{4}$$

or in logarithmic form as

$$\ln k(T) = \ln A - \frac{E_a}{\mathrm{R}T} \tag{5}$$

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

For all exposure temperatures, $k(T)$ was found from the slopes of the linear fits in Figure 2. Next, the degradation constant, $k(T)$, for each temperature was fit to the Arrhenius activation energy theory model (Eq 5), and its dependence on absolute temperature is shown in Figure 4. The straight line is fits to the Arrhenius equation (Eq 5). The results showed a robust fit to the Arrhenius equation (Eq 5) as depicted by the observed R^2 value of 0.90. From the slope of the line, the apparent activation energy was calculated to be 10.8 KJ/mole using Eq 5. These

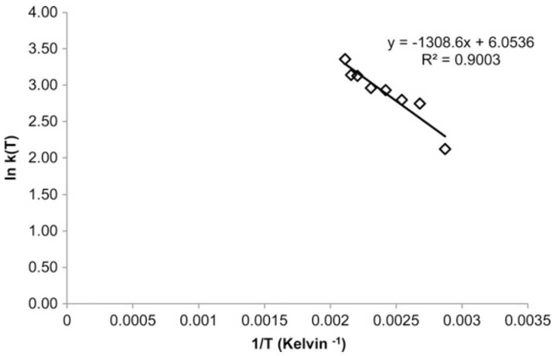


Figure 4. Natural log of $k(T)$ as a function of $1/T$ (absolute) demonstrating a good fit to Arrhenius activation energy theory.

values are lower than the values reported in literature for solid wood, which are 37.4 KJ/mol (Sinha 2013) for Douglas-fir, 59 KJ/mol for southern yellow pine (Lebow and Winandy 1999) and 74-107 KJ/mol for other wood species (Gao et al 2006). For connections, this approach has not been taken before and, therefore, the results could not be compared with similar studies.

Various kinetics-based models have been proposed in the past for degradation of bending strength of solid wood and wood composites (Winandy et al 1991; Sinha et al 2011c). However, no known study has modeled connection yield strength degradation using a kinetics approach. The quality of the fit suggests that a single Arrhenius activation energy can model degradation of yield strength of a connection between wood and OSB from a low temperature (75°C) to 200°C. However, for below 75°C, there will perhaps be too much scatter in experiments to detect the small amount of degradation that would occur in 8 h. Measuring $k(T)$ below 75°C with confidence will require 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.

Comparison of Models

The two models developed, kinetics and regression, were compared for their predictive capacity using an independent previously published data set (Sinha et al 2011a). The data set included Douglas-fir-to-OSB connections of similar specimen and similar dimension and grade tested after exposure to 100°C and 200°C for a period of 1 and 2 h. The difference in the data set was that the shank diameter of the nail used was 3.2 mm instead of the 3.8 mm used in this study. However, the bending yield strength was similar. Six samples were tested under four different time-temperature combinations, and hence, a 24-point data set was available for comparing the models. A goodness-of-fit chi-square test is a statistical tool to assess the predictive capabilities of a model. The chi-square statistic is calculated as

$$\chi^2 = \sum_{i=1}^{n} (E_i - O_i)^2 / E_i \tag{6}$$

It is represented as the sum of squares of difference between the observed and expected results normalized across expected results calculated for each model. The critical χ^2 value is 35 when comparing 24 data points for a probability level of 0.05 (Ramsey and Schafer 2002). A lower chi-square value suggests a better fit. The χ^2 value for a regression-based model was 30, and the corresponding value for a kinetics-based model was 21. It was evident from the χ^2 values that both the proposed models, regression-based and kinetics-based, provided good fits to the independent data sets used for validation. The chi-square value for the kinetics model was much lower than the regression model, which suggested a better fit. The kinetics-based model underpredicted values at 100°C but consistently predicted values at 200°C. In contrast, the regression model consistently predicted values at 100°C but over predicted the 200°C values.

The kinetics model is a two-step process. First, the degradation was modeled to vary linearly with time at a constant temperature (T). The rate of degradation at a constant temperature is $k(T)$. This is similar to the regression model but for a single effect at a given temperature. Then, various rates of degradation for different temperatures were fitted using Eq 2 based on Arrhenius activation theory. This nonlinear dependence of rate (time dependence) with temperature is what distinguished the kinetics-based model from the linear regression model in which a linear, one-step dependence of time and temperature was assumed. Additionally, the kinetics model uses one less parameter than the regression model to predict the yield strength of the connection. The lower χ^2 values suggest that the kinetics-based model should be preferred to the regression models. The measured $k(T)$ and the activation energy here can be used to predict the degradation in connection yield strength of wood at different temperatures and further used to calibrate new models. The predictive models can serve as tools to provide engineers with more comprehensive information on thermal degradation of connections, which will help guide the rehabilitation and retrofit of fire-damaged structures.

CONCLUSIONS

Connection yield strength of Douglas-fir and OSB using a dowel-type fastener degraded with increase in temperature and exposure time. With increase in temperature, variability in the connections yield strength increased. Two models were proposed, one based on statistical regression and the other on the principles of first-order kinetics. Both models showed good predictive capabilities. However, the kinetics model was preferred because of its added predictive capabilities using one less parameter than the regression-based model.

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