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EFFECTS OF SATURATED VAPOR PRE-STEAMING ON DRYING STRAIN IN ASIAN WHITE BIRCH: EXPERIMENTATION AND MODELLING

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ABSTRACT

The effect of low pressure saturated vapor pre-steaming on restrained shrinkage strain, mechano-sorptive creep and the distribution of moisture content was investigated during conventional drying of wood discs. Mechano-sorptive creep was furthermore modelled by artificial neural network theory with five inputs, i.e., pre-steaming and drying temperatures, wood moisture content, relative humidity and distance from the pith. Results revealed that, pre-steaming partly reduced the variation of moisture content distribution along radial direction, increased restrained shrinkage strain in heartwood and decreased in sapwood and slightly decreased the mechano-sorptive creep. The neural network model provided reasonable prediction results, namely, the coefficient of determination for training, validation and test sets greater than 0,95.

Keywords: Artificial neural network, *Betula platyphylla*, mechano-sorptive creep, restrained shrinkage strain, white birch discs.

INTRODUCTION

Numerous studies have been carried out for the improvement of wood drying quality with various pretreatments, such as chemical modification, dry or wet heat treatment. The latter is exposing wood to saturated steam for a period of time just before drying begins (pre-steaming). Pre-steaming has been reported to increase dimensional stability (Fruhwald 2006) and wood permeability (Dashti *et al*. 2012, Ratnasingam *et al*. 2014), reduce moisture gradients within wood (Simpson 1976, Alexiou *et al*. 1990b, Avramidis and Oliveira 1993), and alleviate drying defects (Chafe 1995, Chafe and Carr 1998). Furthermore, some researchers argued that pre-steaming reduced drying time by increasing drying rate (Simpson 1975, Alexiou *et al*. 1990a, Ratnasingam *et al*. 2014), while others reported that pre-steaming reduced moisture content (MC) loss rate (Chafe and Ananias 1996). Avramidis and Oliveira (1993) concluded that pre-steaming had no clear influence on drying rate when hem-fir lumber was pre-steamed at 100**°C** for 5, 10, or 20 hours.

The effect of pre-steaming on shrinkage has been a critical concern. Campbell (1961) considered that relatively short periods of pre-steaming may not significantly alter shrinkage characteristics, but prolonged exposure does cause some changes. Chafe (1990) concluded that pre-steaming resulted in significant increase in shrinkage during oven-dried for 24 hours at 103. Alexiou *et al*. (1990a) reported

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that pre-steaming did not affect volumetric shrinkage. Although there are some studies, albeit conflicting, about the pre-steaming effect on shrinkage, there appears to be no information in the literature about its effect on drying stresses.

It is well documented that drying stresses are the main cause of wood drying defects that greatly affect quality. Better understanding of how drying stresses evolve might allow schedule optimization and defect reduction. Rice and Youngs (1990) investigated the relationship of creep to MC change and load level by using loaded wafers and the slicing method. Some researchers measured drying stresses online in kiln drying process with stress sensors (Allegretti and Ferrari 2008, Ferrari *et al*. 2010). In addition, others developed rheological models to exhibit the evolution of drying stresses and deformations (Salin 1992, Wu and Milota 1995, Märtensson and Svensson 1997, Moutee *et al*. 2007, Salinas *et al*. 2015, Zhan and Avramidis 2017). In recent studies, Larsen and Ormarsson (2013), Larsen and Ormarsson (2014) reported on drying experiments and numerical simulations based on finite element modeling of the moisture-induced stress and strain, but it must make some assumptions.

A large number of comprehensive experiments are needed for determining drying stresses because wood MC, air temperature and humidity change constantly during drying process. Because of procedural difficulties, long times and high costs for this type of experiments, proper modeling becomes paramount. As a powerful tool for modeling without assumptions and knowing a priori the model structure, artificial neural networks (ANN) have been widely used in the field of wood evaluation and processing. Avramidis and Iliadis (2005a), Avramidis and Iliadis (2005b) developed ANN models to predict the thermal conductivity and water sorption isotherms of wood. Tiryaki and Aydin (2014) predicted the compression strength parallel to grain of heat-treated woods indicated that ANN modeling provided high predictive precision, and the R^2 for the testing set was obtained as 0,997%. Watanabe *et al*. (2014) investigated the drying stress at the surface of lumber during drying using near-infrared spectroscopy combined with ANN models.

The aim of this study is to explore the effect of pre-steaming on drying strains and MC distribution in wood during drying process, to understand the controlling mechanisms and to develop an ANN model to predict mechano-sorptive creep in a non-destructive, swift and inexpensive way.

MATERIALS AND METHODS

Materials preparation

One 3-meter-length plantation white birch (*Betula platyphylla*) log (22 years old, average diameter of 23 cm) was collected from Lesser Khingan Mountains in Heilongjiang province of China. Its initial average MC was about 80%, which was determined by oven-dry method.

The log was cut into 30 mm-thickness wood discs, and then sealed in plastic bags and stored in a freezer to prevent water loss and decay. Thirty defect-free wood discs were randomly selected and divided into three groups (10 discs each). In each group, one piece of discs was used to determine moisture content before drying experiment (MC_i), three for determining target moisture content (MC_t), and the remaining six were used for strain measurements. The study was replicated by selecting another thirty wood discs from the original log and repeating the above.

Pre-steaming treatment and drying experiments

Prior to drying, two of the three groups (the third was the control) were pre-steamed with steam/air at 100% relative humidity (dry-bulb and wet-bulb temperatures were equal) at 80^{o}C and saturated vapor at 100°C for 10 hours, respectively. The conditioning was carried out simultaneously in two identical laboratory conditioning chambers (type: GDS-100, Shanghai Scientific Instruments Yiheng Co., Ltd., Shanghai, China). After pre-steaming, three groups of specimens were dried in one chamber with the drying schedule, which is listed in Table 1. The replication experiment was conducted as the mentioned procedures. Before formal drying runs, a preliminary experiment was carried out to acquire the relationship between weight and MC of wood disc. Thus, the approximate MC could be determined immediately by weighing the wood discs, with the oven-dry method as an afterwards verification step.

Table 1: Drying schedule for Asian white birch discs.

Moisture content (%)	Dry-bulb temperature (℃)	Wet-bulb temperature (℃)	Relative humidity (%)	Equilibrium moisture content (%)
>50	40	38	88	18.3
40-35	40	37	82	16
35-30	40	36	76	14.1
30-25	42	35	71	12.7
25-20	43	34	66	11.5
20-15	44	32	57	9.6
15-10	45	30	48	8.2
<10	45	29	44	7.6

Determination of MC and drying strains

MC_i and MC_t were determined from initial weight and oven-dry weight which was gotten by placing specimens in a DHG-9070A drying oven (Shanghai Scientific Instruments Yiheng Co., Ltd., Shanghai, China) at a temperature of 103 ± 2°C until a constant weight. The drying strains, which included shrinkage strain and mechano-sorptive creep, were determined by image analysis method (Fu *et al*. 2015, Fu *et al*. 2016a), it is a noncontact method based on the distance between two dots. A digital camera (1628 × 1236 resolution) was fixed to a tripod, and kept 200 mm from the wood disc under evaluation. Before drying, blue dots were sprayed on the polished surface of the wood discs by oil-based pike at fixed locations (tangential distance between two dots of 20 mm), as shown in Figure 1. As MC_t reached to 28%, 20% and 12% in drying process, one wood disc randomly selected for each group was cut to smaller test specimens (30 × 10 × 30 mm, tangential × radial × longitudinal) for drying strain tests, and consecutive images of the discs (including a scale-plate) were taken before and after cutting. Then, the images were imported into a software called Image J to measure and analyze the actual length of the two blue dots. By comparing the changes of the distance between the two dots, the strain values were obtained.

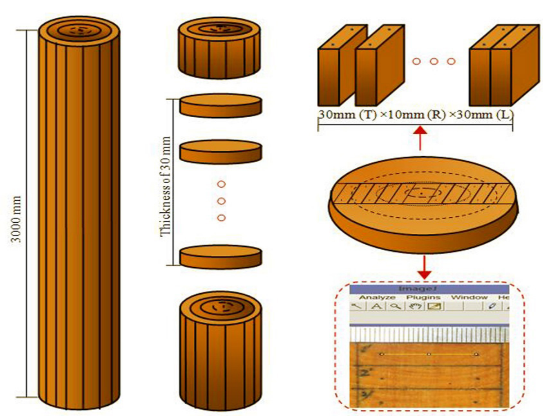

Figure 1: Cutting and testing diagram for wood specimens.

The free shrinkage strain (ε_f), restrained shrinkage strain (ε_s) and mechano-sorptive creep (ε_m) were calculated by the following Equation 1, Equation 2 and Equation 3.

$$\varepsilon_f = (L_0 - L_3) / L_0 \quad (1)$$

$$\varepsilon_s = (L_0 - L_1) / L_0 \quad (2)$$

$$\varepsilon_m = (L_2 - L_3) / L_0 \quad (3)$$

where L_0 is the distance in mm between two dots on the strain specimens before drying, L_1 is the distance in mm between two dots on the strain specimens before cutting at each MC_t, L_2 is the distance in mm between two dots under stable moisture conditions, achieved by placing the strain specimens in a conditioning chamber with equilibrium moisture content equal to MC when the slice shows a split and L_3 is the distance of two dots with the strain slices soaked in water for 24 hours, steamed for 10 h after finishing the test for L_2, and placed in a conditioning chamber to maintain the temperature and humidity conditions in L_2.

Artificial neural network modeling

A feedforward multi-layer perception network as depicted in Figure 2 was used in this study, which comprised of an input layer, an output layer, one or more hidden layers (Avramidis and Iliadis 2005a, Avramidis and Iliadis 2005b, Avramidis and Iliadis 2006, Tiryaki and Hamzacebi 2014). The experimental results were divided into three groups at random without repetitions, namely, the training set (98 test specimens, 60% of the total), the validation set (32 test specimens, 20% of the total) and the testing set (32 test specimens, 20% of the total). To make the transfer function more effective, the input variables and output values are normalized before training the model by means of Equation 4.

$$X' = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \quad (4)$$

where X' is the value after normalisation of vector X, and X_{max} and X_{min} is the maximum and minimum values of vector X.

Pre-steaming temperature, drying temperature, wood MC, relative humidity and distance from the pith were considered as the inputs, whereas mechano-sorptive creep was the output. The number of neurons in the hidden layer was adjusted by trial-and-error during training and validation. The optimal configuration was eight neurons in the hidden layer thus resulting in a 4-8-1 network configuration. The performance of the network was evaluated by the mean squared error (*MSE*), the correlation coefficient (R) and the coefficient of determination (R^2). The Levenberg-Marquardt back-propagation algorithm was considered as the training algorithm. The tangent sigmoid function (Equation 5) in the hidden layer and the linear function in the output layer were chosen as the transfer functions.

$$\tan sig(x) = \frac{2}{1+e^{-2x}} - 1 \quad (5)$$

where tan *sig* (x) is the output value of the neuron; and x is the input value of the neuron.

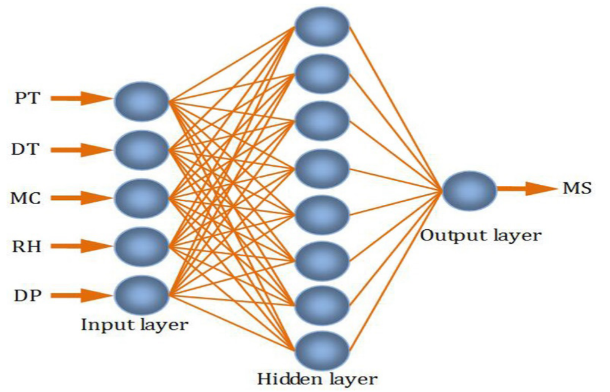

Figure 2: Configuration of the ANN model used for predicting mechano-sorptive creep: PT-pre-steamed temperature; DT-drying temperature; MC-moisture content; RH-relative humidity DP-distance from the pith; MS-mechano-sorptive creep.

RESULTS AND DISCUSSION

Effect of pre-steaming on initial MC and MC distribution

The variation of initial MC from the pith to bark direction and MC distribution after pre-steaming are depicted in Figure 3. There was no obvious uneven distribution of MC along radial direction, except the MC near bark was a little lower than other radial positions. The MC were all decreased after pre-steaming, the MC reduced about 7% and 10% for PS80 and PS100 group, respectively. Four hours of steaming in a saturated steam atmosphere caused a drop of approximately 10% for initial MC reported by Harris (1989). Moreover, the distribution of MC was more even after pre-steaming. As a conclusion, the pre-steaming can reduce the initial MC, and also contributed to the uniform distribution of MC before drying.

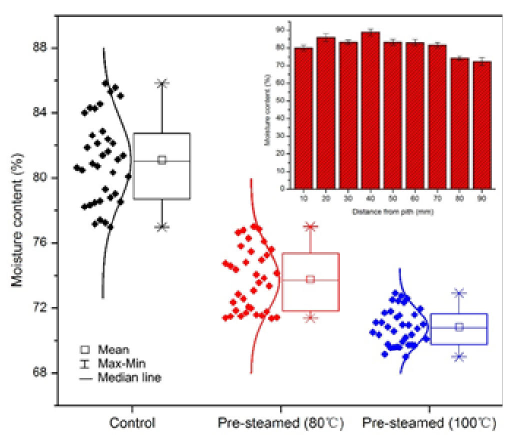

Figure 3: Initial MC along radial direction and MC distribution after pre-steaming.

Figure 4 illustrates the distribution of MC for the control and pre-steamed groups after drying. As shown, the MC distribution was more even in the specimens of the pre-steamed group with the higher treated temperature. For MC_t of 28% (Figure 4a), the difference of maximum and minimum values was 9% for the control, but the value was 6% and 4% for the pre-steamed at 80°C (PS80) and 100°C (PS100), respectively. When drying to MC_t of 12%, the value was reduced to 1% in the control and was less than 1% for pre-steamed groups. The results show that pre-steaming could partly reduce the variation of MC from pith to bark in wood discs, that is reduce the moisture gradient in radial direction, and this will result in better drying quality. This is consistent with past studies where pre-steaming decreased moisture gradients between core and shell (Alexiou *et al*. 1990b, Oliveira and Avramidis 1993). It is probably because pre-steaming improves the permeability and water vapor diffusivity of wood, the specific reasons need further research.

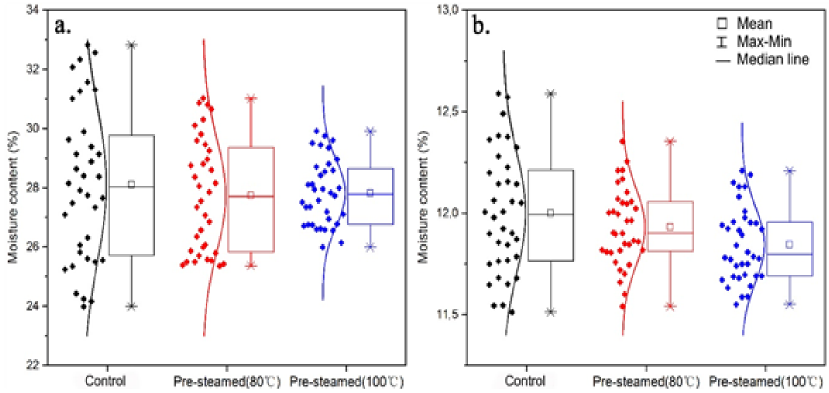

Figure 4: Box plot of MC distribution for the control and pre-steamed wood discs: (a) MC_t of 28%; (b) MC_t of 12%.

Effect of pre-steaming on restrained shrinkage strain and free shrinkage strain

During drying, shrinkage varied in different parts of the specimen due to the non-uniform distribution of MC and the differences in grain direction. For wood discs, the shrinkage in the tangential direction was restrained by the radial direction, and the shrinkage in lower MC parts was retrained by the higher MC parts (Fu *et al*. 2016b). Therefore, the shrinkage strain was not just induced by only the loss of MC, but also due to the restrained drying stresses. The restrained shrinkage strain at different mean MC was shown in Figure 5a. As this figure shows, the restrained shrinkage strain in the control was less than the pre-steamed groups at distances of 10-25 mm and 10-30 mm from the pith for MC_t of 28% and 10%, respectively. However, at 40-90 mm distance, the restrained shrinkage in the control became greater than that in the pre-steamed groups. Thus, pre-steaming increased restrained shrinkage strain in the heartwood, but caused reduction in the sapwood. These can be interpreted as a result of changes in sapwood permeability that were adequate to overcome any weakening of the cell walls through heat effects; in the heartwood, however, extractive easily removed by saturated vapor that consequently, caused an increase in shrinkage (Chafe 1993). Figure 5b depicts the effect of pre-steaming on free shrinkage strain at mean MC_t of 28% and 12%. At MC_t of 28%, the free shrinkage strain in the pre-steamed group was lower than the control. And the free shrinkage strain in PS80 and PS100 group were closed to the restrained shrinkage strain in each corresponding group. However, at MC_t of 10%, the free shrinkage distinction non-obvious for each group.

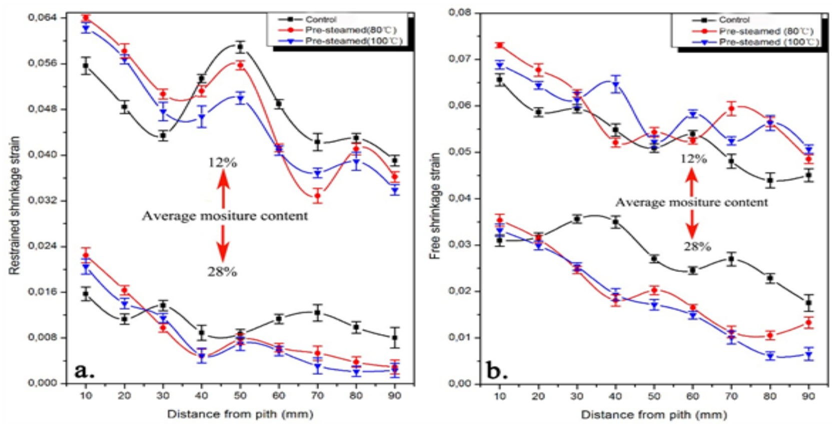

Figure 5: (a) Distribution of restrained shrinkage strain and (b) free shrinkage strain for the control and pre-steamed wood discs at MC_t of 28% and 12% plotted against by the distance from the pith.

Effect of pre-steaming on mechano-sorptive creep

Figure 6 illustrates the distribution for the mechano-sorptive creep obtained in the control and PS80 and PS100. As seen, the mechano-sorptive creep near the pith showed no noticeable changes for different groups and MC. For MC_t of 28%, the tensile mechano-sorptive creep was present at 20-50 mm from the pith, and the creep value in the control was slightly higher than that in the PS80 and PS100 groups. At MC_t of 12%, the higher creep value was still observed in the control for each radial position except to the distance of 10 mm. Thus, the mechano-sorptive creep was slightly decreased with pre-steaming. In addition, the changes of mechano-sorptive creep in PS80 were similar to PS100 group, especially for MC_t of 28%, which showed that the pre-steamed temperature had little effect on mechano-sorptive creep.

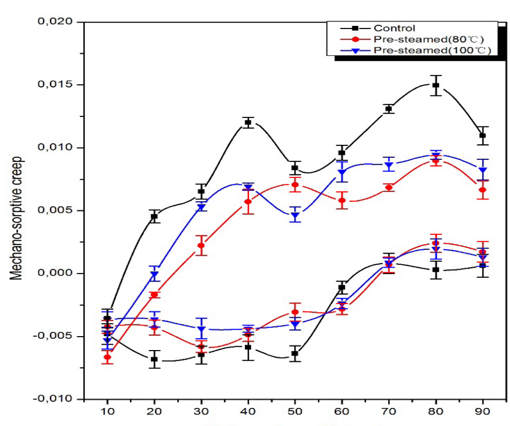

Figure 6: Distribution mechano-sorptive creep for the control and pre-steamed wood discs at MC_t of 28% and 12% plotted against by the distance from the pith.

Prediction of mechano-sorptive creep by the ANN model

As depicted in Figure 7, the *MSE* values in the training, validation and test sets were all close to the goal line. The *MSE* decreased with increased number of iterations, and it achieved the best validation performance of 1,437e-06 at epoch 10.

Figure 8 illustrates the comparison of experimental and predicted values for mechano-sorptive creep at MC_t of 20%. It appears that the predicted values are very close to the experimental ones for all groups, especially in the PS100. This situation proves the reliability of the developed ANN model and gives a good method for predicting other drying strains by using ANN models.

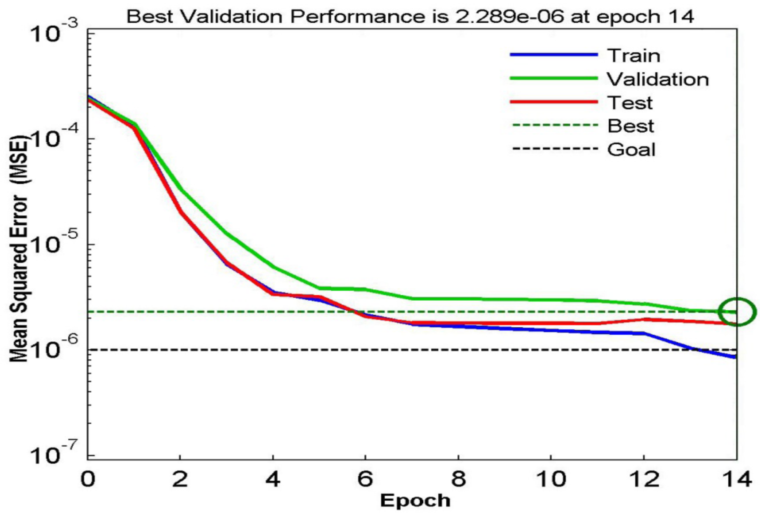

Figure 7: Plot of mean squared error of training, validation and test changes with iteration.

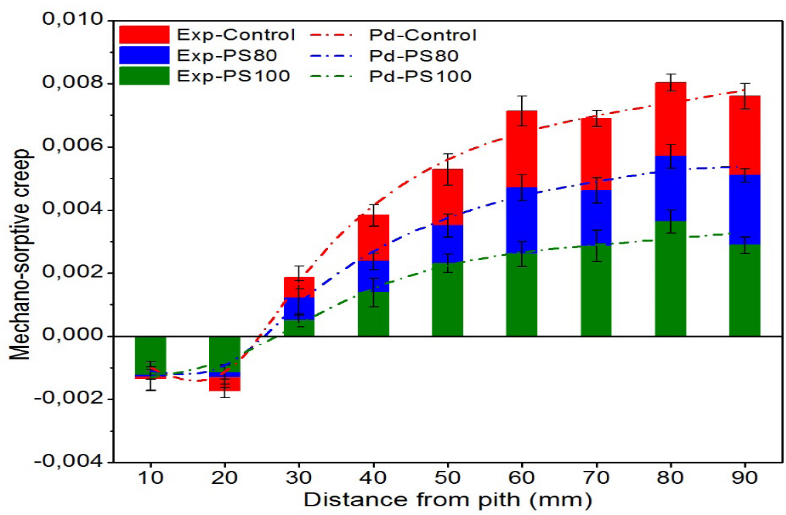

Figure 8: Prediction of mechano-sorptive creep at MC_t of 20% by ANN: comparison of experimental (Exp) and predicted (Pd) value. PS80 indicates pre-steamed at 80°C; PS100 indicates pre-steamed at 100°C

The regression fit between the experimental and predicted values for the training (Figure 9a), validation (Figure 9b) and test set (Figure 9c), in conjunction with their correlation coefficients (*R*) and regression equations are presented in Figure 9. There are significant correlations between experimental and predicted values in all date sets. The *R*-values for training, validation and test sets are 0,979; 0,975 and 0,968 respectively. Furthermore, the R^2 values are greater than 0,95 in the three data sets, indicating that the network model is capable to explain more than 95% of the experimental values. From past studies that used ANNs to predict wood mechanical properties, Esteban *et al*. (2009) determined the modulus of elasticity, achieving 75% success. Tiryaki and Aydin (2014) reported R^2 values were greater than 0,99 for all data sets in predicting compression strength of heat-treated woods.

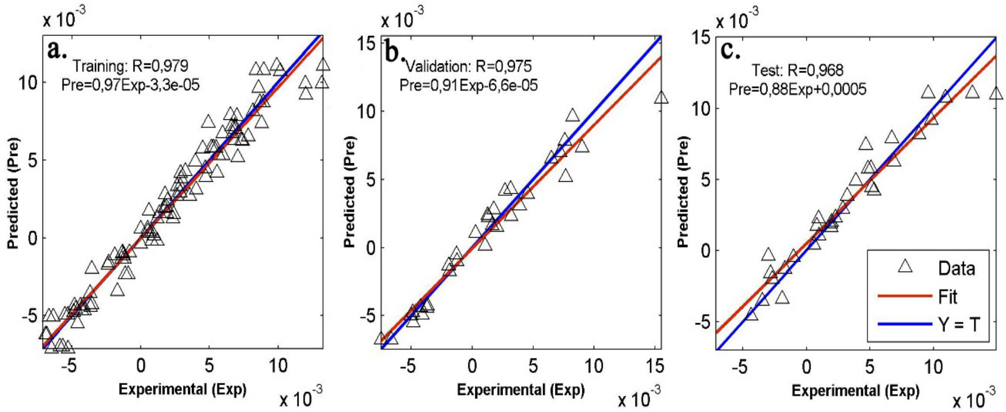

Figure 9: Relationship between experimental and predicted value for training (a), validation (b) and test (c).

CONCLUSIONS

The effect of saturated vapor pre-steaming on restrained shrinkage strain, mechano-sorptive creep and MC distribution in white birch discs was investigated in this study. And the mechano-sorptive creep was predicted by a developed feedforward multi-layer perception neural network.

In summary, the pre-steaming could partly reduce the variation of MC from the pith to bark in wood discs; the pre-steaming caused increase in heartwood but reduction in sapwood for restrained shrinkage strain. Also, the pre-steaming slightly eased mechano-sorptive creep. The distribution of MC along radial in wood discs was uniform after pre-steaming. When the experimental values were compared with predicted ones obtained by the neural network model, the R^2 values were greater than 0,95 for all data sets, showing that ANN can be used successfully for prediction of mechano-sorptive creep of pre-steaming wood. The use of this method is of major importance for reducing time and cost associated to experimentation, and at the same time, it opens up a new field for the prediction of drying strains by neural network modelling.

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