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Applying Stress Waves Velocity for the Evaluation of Physical Properties of Compression–Set Wood

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This study used Taiwan's domestic timber–*Cryptomeria japonica* hot pressed at 180°C for 1 h, and dried at 103±2°C with drying set for 12 h to prepare compression–set wood (CSW). As a control group, compressed wood (CW) was prepared using hot pressing at 180°C for 1 h. The basic properties, compression rate, compression–set rate, thickness recovery (Tr), compression–set recovery (Cr), water absorption, volumetric swelling coefficient, anti–swelling efficiency, and stress wave velocity (Vs) were investigated to realize the difference between the physical properties of CW and CSW. The physical properties of CSW compressed from 22, 24, and 27 mm to 18 mm with drying set had better dimensional stability than those of CW. The higher dimensional stability of CSW is related to the elasticity and plasticity of wood. The wood is upgraded from the elastic zone to the critical point of elastic and plastic zones by compression setting to reach a fixed size effect. In other words, the Tr is decreased without damaging the mechanical properties. The correlation coefficient (r^2) of Vs and CSW with Tr below 3% approaches 0.0, and the r^2 of the Tr of 6–8% was higher than 0.7. After the compression–set recovery test, the r^2 of Cr and Vs of CW and CSW was higher than 0.8, representing a higher correlation. This Vs is able to be applicable for evaluating the physical properties of the woods with large dimensional changes in thickness, as this change can be related to the wood porosity. In summary, the CSW has good physical properties, the dimensional instability of CW can be improved, and the Vs can be used for evaluating the physical properties of CW and CSW.

Key words: Compression–set Wood (CSW), Compressed Wood (CW), Physical Properties, Stress Wave Velocity (Vs), *Cryptomeria japonica*

INTRODUCTION

Taiwan has abundant forest resources, cutting down natural forests is universally prohibited for the protection of forestry from 1980, more than 99% of wood is imported, and the timber self–sufficient ratio is lower than 1% (Forestry Bureau, 1995). To increase the timber self–sufficient ratio, the Forestry Bureau proposed "the first year of domestic timber" in the 2017, restarted Taiwan's plantation forest operation, and promoted the utilization of domestic timber. According to the 4th Forest Resources Investigation Report (2016), the plantation timber storage is about 64.49 million m^3, accounting for 12.8% of Taiwan's forests. The *Cryptomeria japonica* (Japanese cedar) is the majority, accounting for 40% of plantation coniferous forests. However, most of the Taiwan's domestic Japanese cedar are medium and small woods of thinning, including a high proportion of immature wood. The physical and mechanical properties of Japanese cedar are underutilized. There are many restrictions in practice, leading to low value and utilization.

Compressed wood (CW) is an improvement method on wood properties. Light, soft, and low–density wood species are modified into high–density and high–strength materials. After hot pressing, densification can be observed on the wood surface. Specific gravity and hardness are increased, resulting in higher mechanical properties than wood (Seborg, 1945). The CW performs spring back due to ambient moisture, leading to dimensional instability. This reverts the physical and mechanical properties to that of untreated timber. Inoue (1991) indicates that the wood recover after hot pressing, and a shorter hot pressing time at a constant temperature leads to a higher thickness recovery (Tr, mm) or spring back (%). This means that the Tr or spring back of CW is related to the hot pressing temperature, pressure, and time.

Inoue *et al*. (1993; 2008) indicate that after the heat treatment, the cells of wood absorbed moisture, the Tr can be decreased by drying and steam heating. Dwianto *et al*. (1998) and Ito *et al*. (1998) indicate that after partial hydrolysis of the amorphous region of cellulose, the hydrolyzed components were rearranged by the vapor into a new crystal area. Using this process, the wood remained integral and the Tr after compression can be decreased effectively. The dimensional stability and durability of wood can be enhanced. Inoue (1991) indicate that the capacity of water absorption for wood can be decreased by heat treatment. The equilibrium moisture content in wood can be reduced by more than 50%. The heat treatment temperature of about 190°C can decrease the water absorption of Japanese cedar to the maximum extent, and the dimensional stability can be improved.

The sound waves and stress wave methods are the most frequently used nondestructive detection tests. According to Lin *et al*. (2001), the relationship between

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the elastic modulus and flexural elastic modulus of stress fluctuation is relatively high. The stress wave propagation in wood is related to its physical and mechanical properties (Lin *et al.*, 2002; Lin and Huang, 2003). The micro destruction inside the specimen during hot pressing of CW is detected by stress wave. The internal moisture after moisture absorption increases the porosity, leading to Tr. The variance in the internal microstructure after CW recovery and stress wave velocity might be applied in further (Inoue *et al.*, 1993; 2008). The CW recovery might be related to the elastic and plastic zones of wood. When the wood is only loaded in the elastic zone, it is likely to recover due to time or environmental factors, and it is unlikely to fix the size. When the wood is partially loaded in the plastic zone during the compression–set process at controlled temperature, pressure, and time, the wood recovery can be decreased effectively. The surface is densified, the water absorption is decreased, and the dimensional stability, of wood, can be enhanced (Ito *et al.*, 1998).

To improve the water absorption and compression-set recovery (Cr, %) of CW resulting from the environment and dimensional instability and to investigate the relationship between the physical properties and stress wave velocity (Vs) in the CW and CSW through compression–set recovery test, the domestic Japanese cedar from Taiwan, used as the specimen, was hot pressed at 180°C for 1 h and prepared into CW, drying set in the mold, and dried in the oven for 12 h to make the compression–set wood (CSW). The Cr of CW was decreased through a long–term treatment to fix the size. The dimensional stability was enhanced. Afterward, the dimensional stabilization of CSW was evaluated by the volumetric swelling coefficient, anti–swelling efficiency, and water absorption in water immersion test. The correlation between the physical properties and Vs of CSW before/after the compression–set recovery test was investigated. This is to assess the feasibility of Vs as physical properties of CSW and to provide a reference for the physical modification of plantation forest of Taiwan's domestic Japanese cedar hopefully.

MATERIALS AND METHODS

Experimental materials

The Japanese cedar were taken from Fenchi Lake 141 Compartment of Chiayi Forest District Office, Taiwan. Sound wood was selected as the specimen. It was cut into 325 length x 65 mm width in the longitudinal section with 22, 24, and 27 mm thicknesses in the radial direction. These specimens were air-dried for future use.

Test methods

Preparation of CW and CSW

The specimen was preheated at a hot pressing temperature of 180°C and hot pressed at the same temperature for 1 h. Afterward, the CW was put in a drying setting mold (designed by this study), and a torque wrench fastened the nut with 450 kgf–cm torque to an 18 mm thick gauge block. The hot pressed specimen was fixed into the mold and placed in the oven for drying setting at 103±2°C. After 12 h drying setting treatment, the CSW was prepared.

Determination of physical properties of CW and CSW

1. The moisture content (MC, %) of CW and CSW was determined according to CNS 452 Wood – Determination of moisture content for physical and mechanical test.

2. The density (g/cm^3) was determined according to CNS 451 Wood – Determination of density for physical and mechanical tests.

3. Compression rate (C, %): it is determined referring to the test methods of Inoue *et al.* (2008) and Esteves *et al.* (2017). Compression rate C (%) = (thickness before densification – thickness after densification) / thickness before densification ×100

4. Thickness recovery (Tr, mm): the thickness in the recovered state was measured at intervals of 0.5, 1, 2, 8, 12, 24, and 24 h.

5. Compression-set rate (Cs, %): it refers to the compression–set test method of Esteves *et al.* (2017). Cs (%) = (thickness before densification – thickness after densification + drying setting) / thickness before densification ×100

6. Compression–set recovery (Cr, %): it is determined referring to the compression–set recovery test of Inoue *et al.* (2008) and Esteves *et al.* (2017). Cr (%) = (Lcycle–Lafc) / (Locr–Lafc) ×100
   Where Locr was absolute–dried thickness before compression (mm),
   Lafc was absolute–dried thickness after compression (mm),
   and Lcycle was thickness after each cycle (mm)

7. Dimensional stability: it refers to the water immersion test method of Lu and Lin (2008), and Kuo and Lu (2012). the test method for determining the water absorption, volumetric swelling coefficient, and anti-swelling efficiency. The equations are as follow:
   a. Water absorption (WAP, %)

$$WAP(\%)=\frac{W_W-W_0}{W_0}\times 100$$

   Where W_w is the weight (g) of specimen in a water–saturated state, and W_0 is the absolute–dried weight of specimen (g)

   b. Volumetric swelling coefficient (S, %)

$$S\ (\%)=\frac{V_W-V_0}{V_0}\times 100$$

   Where V_w is the volume of specimen in a water–saturated state (cm^3), and V_0 is the absolute–dried volume of specimen (cm^3)

   c. Antiswelling efficiency (ASE, %)

$$ASE\ (\%) = \frac{S_c - S_t}{S_c} \times 100$$

Where S_c is the volumetric swelling coefficient of CW after the water immersion test, and S_t is the volumetric swelling coefficient of CSW after the water immersion test

Evaluation of stress wave detection technique

The longitudinal sound velocities of test materials were determined by a stress wave meter (FAKOPP Microsecond Timer). The uncompressed test material, CW, and CSW were conditioned at a constant temperature and humidity room to a temperature below 70°C, and placed on the stress wave template (designed by this study). The pulse generator and receiver were directly inserted into both ends of the specimen (insertion angle should be 45–60°) and knocked by a hammer (Lin *et al.*, 2002; Lin and Huang, 2003). The time of stress wave transmission through the specimen and the stress wave transmission distance was measured at intervals of 0.5, 1, 2, 8, 12, 24, and 24 h. The stress wave velocity (Vs) was calculated using the following equation.

Vs (m/s) = d/t

Where Vs is longitudinal stress wave velocity (m/s), d is specimen length (m), t is time (sec)

Statistical analysis

The result was represented by the mean (standard deviation). The Statistical Product and Service Solutions (SPSS) 12.0 statistical software was used for Duncan's multiple range test to compare the CW with CSW in compressed time, C, Cs, MC, density, Tr, and ASE. The linear regression equation and correlation difference (r^2) was investigated on Tr and MC, Tr and Vs, as well as Cr and Vs by linear dependence.

RESULTS AND DISCUSSION

Effect of compressed and compression–set rates

The 22 mm thick control group was compressed into an 18 mm thick CW and CSW, with a 15–16% C and Cr. The 24 mm specimen was compressed into 18 mm CW and CSW with a C and Cr of about 22%. The 27 mm specimen was compressed into 18 mm CW and CSW with C and Cr of about 30% (Table 1). The Tr of specimens after compression were influenced by C and Cr. For example, the spring back (%) of the specimens with the C and Cr of 67% and 17% are 88.9% and 95.0%, respectively. The C and Cr influences the strength quality of CW. The internal stress of wood at the initial stage of compression increases with C and Cr, and the wood is in elastic deformation state at this point. When exceeding the proportional limit, the stress is stabilized to some extent and increases rapidly when the C and Cr increase to 55%. The wood cells are likely to be crushed under this condition, and the strength us decreased (Inoue *et al.*, 2008). The C influenced the Tr of CW, and the Tr decreased as the C and Cr increased (Fig. 1). The C and Cr influences the strength quality of CW. When exceeding the proportional limit of the elastic zone of wood, the plastic zone of wood is damaged, and the mechanical properties are degraded rapidly (Hwang, 1997).

Effect of moisture content

The MC in all specimens before compression and compression-set was 11–13%. There was no significant difference according to Duncan's multiple range test. After three weeks of CW and CSW of the specimens, the MC was decreased to 5–8%. The MC in CW was reduced by about 40%, and that in CSW was reduced by about 50% (Table 1). Therefore, the moisture absorption of wood cells might be decreased effectively by using a compression setting to densify the wood surface. Pelit *et al.* (2017) indicate that moisture absorption of the densified test material decreases as the increase of temperature and dimensional stability. The chemical compositions and structure of wood change during hot pressing. The hydrophilic OH in the hemicellulose decreases, and the cellulose and lignin might perform cross–linking reactions (Homan *et al.*, 2000; Kocaefe *et al.*, 2008). The amorphous region of wood absorbs moisture. The

Table 1. Compression and compression–set rate, and moisture content, density of compressed wood and compressed–set wood

Specimen[1)]	Compression/ Compression–set rate (%)	Uncompressed moisture content (%)	Compressed moisture content (%)	Uncompressed density (g/cm^3)	Compressed density (g/cm^3)
22–CW	15.73 (0.50)[a2)]	12.12 (0.84)[a]	7.38 (0.04)[a]	0.34 (0.02)[a]	0.41 (0.06)[aA3)]
24–CW	22.20 (1.38)[b]	12.32 (0.97)[a]	8.15 (1.76)[a]	0.34 (0.05)[a]	0.45 (0.12)[aC]
27–CW	29.76 (1.96)[c]	12.25 (0.62)[a]	7.61 (0.61)[a]	0.38 (0.01)[a]	0.48 (0.04)[aE]
22–CSW	15.52 (1.01)[a3)]	12.38 (0.86)[a]	6.61 (0.77)[a]	0.36 (0.09)[a]	0.44 (0.03)[aA]
24–CSW	22.57 (1.48)[b]	12.59 (0.41)[a]	6.46 (1.02)[a]	0.35 (0.05)[a]	0.57 (0.03)[bC]
27–CSW	30.64 (0.92)[c]	11.57 (0.42)[a]	5.84 (0.21)[a]	0.36 (0.07)[a]	0.62 (0.04)[bE]

[1)] 22–CW: thickness – Compressed Wood; 22–CSW: thickness – Compression–Set Wood

[2)] CW: Compression rate (%); CSW: Compression-set rate (%), Mean (Standard Deviation), a, b, and c show significance within lengthwise difference ($P<0.05$), according to Duncan's multiple range test

[3)] A and B show significance within 22–CW and 22–CSW difference; C and D show significance within 24–CW and 24–CSW difference; E and F show significance within 27–CW and 27–CSW difference ($P<0.05$), according to Duncan's multiple range test heat can increase the non–moisture absorbing crystalline regions in the crystal region (Ito *et al*., 1998; Navi and Heger, 2004) to enhance the hydrophobicity of wood. In this study, as the CW was heated, the hydrophilic OH in the hemicellulose was decreased, and the non-moisture absorbing crystalline regions were increased. The hydrophobicity of wood and the dimensional stability; therefore, were enhanced.

Effect of density

The densities of all specimens before compression and compression–set ranged between 0.3 and 0.4 g/cm^3, with no significant difference (Table 1). The specimens after compression and compression–set, and then placed

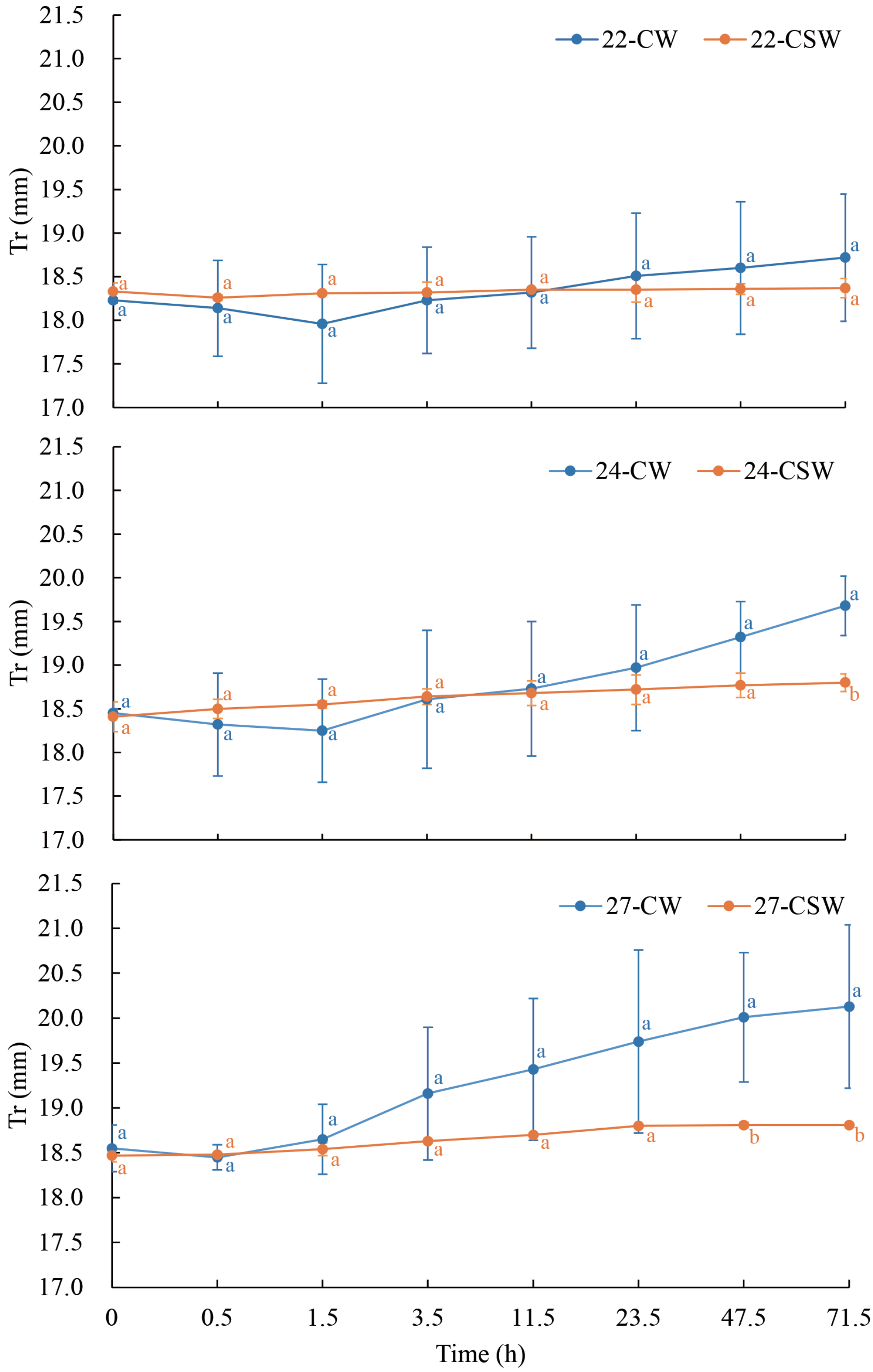

Fig. 1. Relationships between time and thickness recovery (Tr) for compressed wood and compression–set wood
Note: 22–CW and –CSW see Table 1; a and b show significance difference (P<0.05), according to Duncan's multiple range test

for more than three weeks. The density of 22–CSW, 24–CSW, and 27–CSW was increased by 22.22, 62.86, and 72.22%, respectively. The density of CW and CSW increased with C and Cr. Inoue *et al*. (1993) indicate that the density increases from 0.36 to 0.50. This reflects an increase of about 39% when the compression was 30%. When the compression was 60% and the specific gravity is increased to 0.90, the density was increases by about 150%, and the hardness increases from 0.07 MPa to 0.25 MPa due to compression, about a tripling increase. Hwang (1997) indicates that the MOE and MOR of CW increase with CW density, the wood density is increases after compression, and mechanical properties such as hardness, MOE, and MOR, are enhanced accordingly.

Relationship between thickness recovery and time

The 22–CW and 22–CSW were placed under the atmosphere for 71.5 h. The Tr were 18.72 and 18.37 mm with no significant difference (Fig. 1). The Tr of 24–CW and 24–CSW were 19.68 and 18.8 mm, respectively with a significant difference. The Tr of 27–CW and 27–CSW were 18.81, 20.01 mm, and 18.81, 20.13 mm, respectively, with significant differences. The CSW with Tr of 24 and 27 mm had better dimensional stabilization than CW. The overall standard deviations of Tr of 22–CW, 24–CW, and 27–CW were higher than those of 22–CSW, 24–CSW, and 27–CSW because the Tr of each specimen after the compression–set was smaller and with a higher stabilization. The thickness variation of each specimen with compression (without drying set) was larger. In summary, when the specimen thickness was 22 mm, the thickness variation of CW and CSW under the atmosphere was not large. The CSW in thicknesses of 24 and 27 mm had better dimensional stabilization than CW. The standard deviation of the Tr of CSW was less than that of CW. The specimens of CSW had a small Tr difference and relatively stable distribution.

Relationships of thickness recovery to moisture content and density

The MC increases as the wood absorbs moisture and changes size. The thickness swelling can be decreased effectively by reducing the water absorbing capacity of wood and the equilibrium moisture content in the wood (Hwang, 1997). As shown in Fig. 2, the correlation coefficient (r^2) of the specimens other than 24–CSW was smaller than 0.40, representing a low correlation. The increase in the Tr of specimens under the atmosphere did not result from the increase in MC. The r^2 of Tr and density of 22–CW, 24–CW, and 27–CSW were 0.11, 0.01, and 0.34, respectively, representing a low correlation. The r^2 of 22–CSW and 24–CSW were 0.58 and 0.65, representing a significant correlation. The r^2 of 27–CW was 0.75, representing a high correlation. When the control groups were 22 and 24 mm, the Tr–density correlation of CSW was higher than that of CW. The r^2 of 27–CW was larger, suspected to be related to the larger Tr. The increase or decrease in the Tr of specimens is slightly influenced by the MC and density. Hence, the dimensional stabilization of the CSW, compression-set with drying set, can be evaluated by the specimen Tr.

Relationship between stress wave velocity and recovery

The correlation coefficient r^2 of the Vs and Tr of 22–CSW, 24–CSW, and 27–CSW and Vs gradient were close to 0.0, representing no correlation. The r^2 of 22–CW was

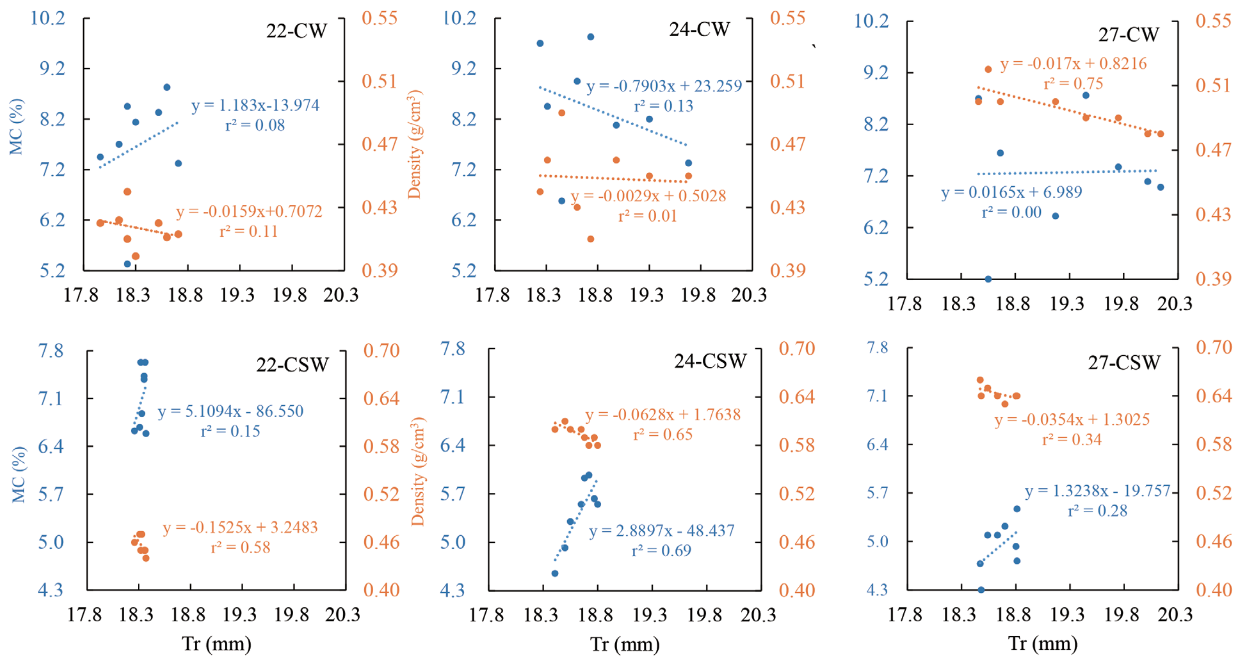

Fig. 2. Relationships among thickness recovery (Tr), moisture content (MC), and density for compressed wood and compression-set wood

Note: 22–CW and –CSW see Table 1

0.43, representing a slight significant correlation. The r^2 of 24–CW and 27–CW were higher than 0.70, representing a high correlation (Fig. 3). The specimens after the method of compression–set had a low Tr, which was uncorrelated with Vs. The 24–CW and 27–CW had a higher Tr, which was highly correlated with Vs. Therefore, according to the correlation, the CSW had a better dimensional stabilization than CW. It is said that the Vs is able to be used for evaluating the physical properties of the materials with large thickness (Tr) variations.

Relationship of compressed/compression–set recovery to stress wave velocity

The CSW in Cr of 22, 24, and 27 mm had a lower compressed recovery in each cycle than CW. Therefore, the CSW had a better dimensional stabilization than CW

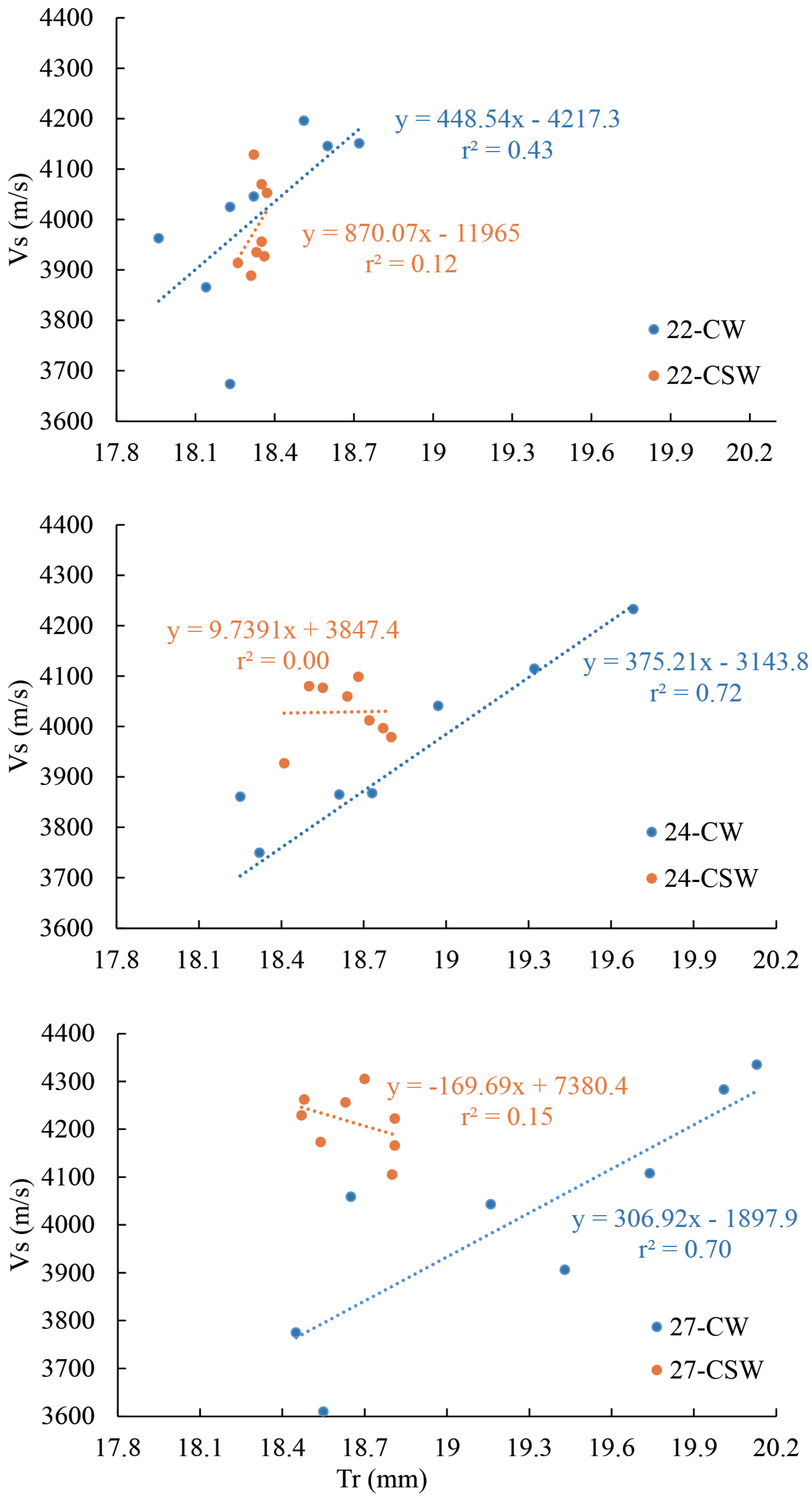

Fig. 3. Relationship between thickness recovery (Tr) and stress wave velocity (Vs) for compressed wood and compression–set wood
Note: 22–CW and –CSW: see Table 1

after the water immersion test (Esteves *et al.*, 2017). The method of compression–set developed the wood move from the original load elastic zone up to the critical point of elastic and plastic zones. The specimen was unlikely to recover, and the strength property was not damaged. The Cr of 27–CSW in the third cycle was 49.45%, lower than the compressed recovery in the first cycle of the others. This might be because the CSW load had exceeded the elastic limit and reached the plastic zone of wood, and the wood could not recover. The strength property in this state was a little damaged (the result is not shown in the figure). Therefore, the CSW was upgraded from the load elastic zone to the critical point of elastic and plastic zones. The size was fixed and the Cr was decreased without damaging the strength property. As all of the specimens exhibited the same

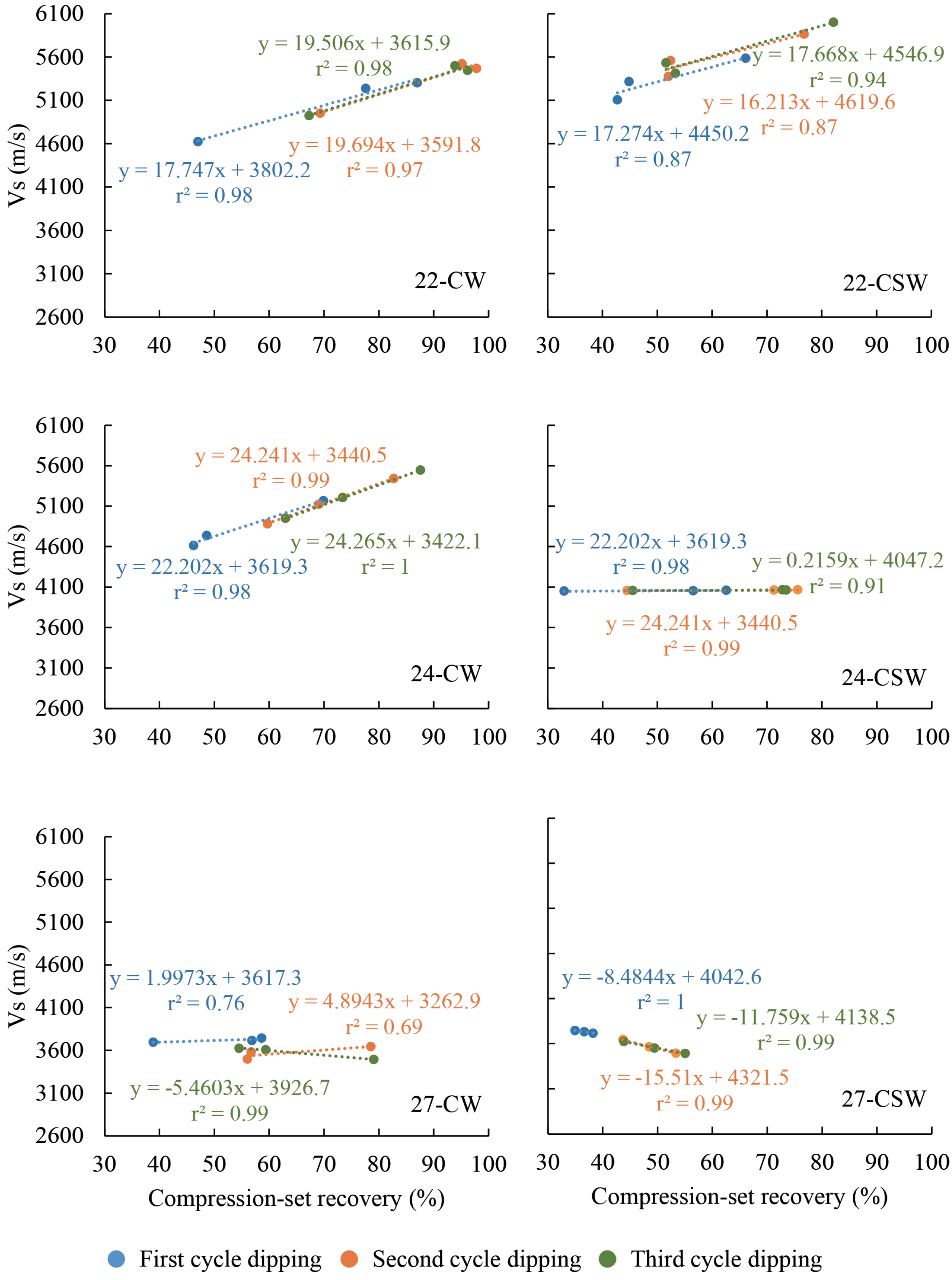

Fig. 4. Relationship between compression-set recovery and stress wave velocity (Vs) for compressed wood and compression–set wood

Note: 22–CW and –CSW see Table 1

trend line, only the first and second cycles were required to be tested in future compression–set test. The correlation coefficient r^2 of Vs and the Cr of all specimens was about 0.70, indicating a high correlation (Fig. 4). When the specimen was immersed in water, the thickness swelled, the medium in the porosity changed, and the Vs was influenced. The Cr of 27–CSW was negatively correlated. This could be because the compression–set loaded the wood under the plastic zone.

Water absorption, volumetric swelling coefficient, antiswelling efficiency

The water absorption of the CSW in thickness of 22, 24, and 27 mm after hot pressing was lower than that of CW (Table 2). The surfaces of CW/CSWs were densified by the compressed methods. The water absorption of wood cells could be decreased effectively, and the wood recovery was decreased. Hsu *et al*. (2000) indicate that the spring back can be effectively decreased by surface densification, which is 0.5–0.7% of the thickness. The water absorbing capacity of wood is decreased, and the lignin glass transition point is reached in the hot compression–set process. The lignin is softened and the elastic stress inside the wood can be partially eliminated to achieve better antiswelling efficiency (Johansson, 2005). The antiswelling efficiency of 22–CSW, 24–CSW, and 27–CSW was 20.04, 23.60, and 24.64%, respectively, which increased with compressibility. The 24–CSW and 27–CSW had no significant difference.

Table 2. Water immersion test results of compressed wood and compression–set wood

Speicmen[1)]	Water Absorption (%)	Volumetric swelling coefficient (%)	Anti–swelling efficiency (%)
22–CW	208.41 (32.40)	25.69 (1.69)	–
24–CW	212.66 (21.90)	29.84 (1.34)	–
27–CW	190.47 (13.45)	38.58 (3.29)	–
22–CSW	172.07 (37.80)	20.26 (3.14)	20.04 (0.87)[a2)]
24–CSW	185.57 (14.80)	24.56 (5.62)	23.60 (0.98)[b]
27–CSW	167.57 (4.96)	29.10 (2.94)	24.62 (0.98)[b]

[1) and 2)] see Table 1

CONCLUSION

The Japanese cedar, one of the domestic timbers in Taiwan, was prepared into CSW in this study. CW was used as the control group to compare their basic properties, physical properties, and the feasibility of using Vs to evaluate the physical properties of CSW. The results were concluded below:

1. The wood surface was densified by the method of compression–set, and the water absorption of wood cells were able to decrease effectively.
2. The densities of 22–CSW, 24–CSW, and 27–CSW were increased by 22.22, 62.86, and 72.22%, respectively. The density increased with the method of compression–set.
3. CSW in the thickness recovery Tr of 24 and 27 mm had better dimensional stabilization than CW. It is suggested that the wood is upgraded from the load elastic zone to the critical point of elastic and plastic zones by the method of compression–set.
4. The correlation coefficient r^2 of stress wave velocity Vs and the compression–set recovery Cr of CSW had a high correlation.
5. The CSW had lower water absorption and volumetric swelling coefficient than CW. The antiswelling efficiency was 20.04–24.62, which increased with the method of compression–set.
6. As the stress wave velocity Vs was highly correlated with the compression–set recovery Cr of CSW, it is feasible to evaluate the physical properties of CSW.

AUTHOR CONTRIBUTION

Zhu Ming Tang, and Yu–Ting Lin performed the course/experiments and evaluated data with the statistical analysis. Noboru Fujimoto supervised the work. Han Chien Lin designed the study and wrote this paper. The authors assisted in editing of the manuscript and approved the final version.

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