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Influence of Thermo-Mechanical Densification (TMD) on the Properties of Structural Sawn Timber (*Pinus sylvestris* L.)

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Abstract: The article presents the results of thermo-mechanical densification tests conducted on Scots pine timber. The densification process was carried out in industrial conditions with a high-pressure press, which allowed flat compression of boards that were up to 2,5 m long. A phenomenon of elastic redeformations was observed in the densified boards after each pulse of compression. As a result of thermo-mechanical compression, the average timber moisture content dropped to 9%, and the average density increased by 13.5%, from the level of 547 to 621 kg/m^3. As a result of thermo-mechanical densification, the strength class C of most Scots pine timber pieces improved. Most timber pieces that were subjected to thermo-mechanical densification have improved their strength class, C, by one (72.7% of the tested batch) or two C classes (3.6% of the batch under study).

Keywords: density; MOE; strength grading; structural timber; TMD

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1. Introduction

The growing demand for wood and engineered wood products for construction and the limited availability of high-quality wooden resources have stimulated the search for new, alternative materials to use in construction. One of the possible directions to solve the problem of raw materials is to develop treatments and processes to modify conventional materials in order to complement or replace the domestic forest species [1]. One of the factors of an effective economy that takes into account the need to simultaneously mitigate climate change is an ecologically sustainable wood treatment that consists of exposing it to appropriate temperature and pressure at the same time, without the need to add any chemical substances [2,3]. Thermo-mechanical treatment (TMD) of wood is a process of densification that has been known for decades and results in the increase of material density through compression perpendicular to the grain [4]. The density of wood and engineered wood products (EWP) is one of the criteria for conditioning the technical quality of a material. In general, wood species and EWP with greater density are preferred for many applications in the construction industry, due to their higher resistance and natural durability [5]. However, the availability of high-density wood is limited, and as a result, their purchase requires significant financial spending. Therefore, the use of wood with low or medium density subjected to a process of densification can improve its technical parameters, while at the same time taking into account the aspect of affordability.

There are many premises that justify the application of TMD as a structural timber modification process. For example, exposing wood to high temperatures increases its resistance to biological factors [6–9] and its dimensional stability [10,11], and reduces its hygroscopicity [12–15]. By adding the compression (densification) process, we can improve the physical and mechanical properties of wood [16–20]. As a result of the surface densification of wood, it is possible to increase its hardness even twice [21] and significantly improve the durability of the material. These features translate into the potential for the application of densified wood, especially in external layers of layered floor materials [22–24]. The concept of using a material that was initially worse, and whose resistance properties improve after modification, is especially important in the case of wood with low initial density, such as poplar [25,26], coniferous species [27,28], or eucalyptus [29,30]. One of the areas where wood with originally worse quality can be used is construction. As a result of the densification of spruce wood, it is possible to improve both MOE and MOR by up to 200%–300% in comparison with native (not densified) wood [31,32]. In the case of pine sapwood, the MOE of wood subjected to thermo-mechanical treatment amounted to 14.4 GPa (a 150% increase compared to native wood), while its density incremented from 385 kg/m^3 to 1040 kg/m^3 [33]. Similar results have been obtained for pine wood by Esteves et al. [34], who densified wood between press shelves at temperatures of 150°C, 180°C, and 200°C. Wood with an initial density of 615 kg/m^3, 614 kg/m^3, and 512 kg/m^3 after densification achieved the following values: 1048 kg/m^3, 1031 kg/m^3 and 1041 kg/m^3, respectively. The MOE of densified wood was higher than native wood by 42%, 40%, and 71%, respectively. In the case of spruce wood, at a compression rate (CR) equal to 22%, 50%, 60%, and 67%, the density increase of native wood was in the range between 33% and 78%, while the elasticity modulus was between 79% and 114% [35]. Excessively elevated temperatures in the densification process affect the mechanical properties of wood negatively. This can be caused by the growing chemical degradation, which exacerbates together with rising temperatures. The most optimal temperature level for densification is considered to be 120 °C. For pine wood, a densification process performed at a temperature of 120 °C resulted in an 85% density increase, leading to an improvement of bending strength by 42%, shear strength by 20%, and compressive strength by 47% [35]. In the case of poplar wood, depending on the treatment temperature (120–200 °C), wood density increased by 144%–188%, which translated into an MOE that was 73%–130% higher and MOR higher by 3%–72% [36]. As to sugi wood, the densification process allows us to achieve an MOE increase by even 309%, and MOR by up to 183% [37]. TM wood processing is a scientific field that has been well-studied, which is confirmed by multiple literature publications on this topic, focusing on analysing the influence of CR, steam temperature, pressure, species tested, the direction of compression, etc. Nonetheless, it should be taken into account that most studies were carried out on small samples, at a laboratory scale, which—of course—does allow us to observe the influence of a given factor on the densification effect or lack thereof. However, study results obtained at a laboratory scale, looking at the physical and mechanical properties of wooden samples, can be affected by the so-called scale effect [38], which is a very important aspect when it comes to considerations of wood applications in engineering. In the stochastic aspect, the higher the volume of a wooden element (laboratory/full-scale technical sample), the higher the probability of defects in the structure of the wood.

Nevertheless, the high effectiveness of thermo-mechanical treatment, confirmed by the improvement of physical and mechanical properties of wood, allows us to conclude that with appropriate scaling and adjustment of treatment parameters, the process of wood densification can be used to enhance wood quality, not only in timber from plantations but also in traditional, domestic species, whose average density values are low, which will allow for their use in construction applications (as independent structural elements or for the production of layered composites). One of the necessary conditions for safe building with timber is the use of wood with adequate strength parameters. Sawn timber used in construction for structural purposes must be subjected to strength grading. There are two methods for strength grading of structural sawn timber: visual and machine. Machine strength grading results in much higher efficiency and wood pieces are classified into higher classes, with fewer timber pieces rejected in comparison to the results of visual strength grading of the same batch of wood [39]. As a result of machine strength grading, the timber pieces are classified into C strength classes in accordance with the EN 338 standard [40].

The study described herein refers to the analysis of the effects of thermo-mechanical timber densification in industrial conditions on the selected physical and mechanical properties of wood. The technical scale of the study permits us to directly apply the obtained results to the characteristic resistance of wood, corresponding to a given sorting class and C strength grade [40]. It is also possible to specify the structure of C strength classes of a given batch of timber before and after densification, which has both an economical and ecological dimension.

2. Material and Methods

The study was conducted on a batch of boards made of pine wood (Pinus silvestris L.) that contained 400 pieces with an average moisture content of 13%. The timber originated from the Masovian Forestry Region (central Poland). The nominal board dimensions were: 24 x 90 x 2400 mm. The boards had a flatsawn growth ring layout (tangential sections on the wide board surfaces). The average growth ring width amounted to 1.50 mm, and timber was obtained from sapwood, with a small share of resin substances and a low amount of knots.

The scope of the research included: specifying the values of density (DEN), dynamic modulus of elasticity before thermo-mechanical modification (MOE), the performance of thermo-mechanical timber modification in industrial conditions, as well as specifying the density and modulus of elasticity of modified timber (DEN_{TMD}, MOE_{TMD}). The density of the timber under examination was determined with the stereometric method. The determination of the modulus of elasticity was carried out with the MTG device (Brookhuis Microelectronics BV, Holland). The device uses the impact method to determine MOE_{dyn}. The machine was also used for the strength grading of the timber batch under research before and after thermo-mechanical modification. The density profile of sample planks was determined with the use of a profile meter: Laboratory Density Analyser DAX GreCon (Fagus-Grecon Greten GmbH & Co. KG, Alfeld, Germany). A density measurement was made every 0.02 mm at the measurement speed of 0.05 mm/s. Before the test, the samples used to determine the density profile were planed on both sides to avoid any concave or convex areas on the wide surfaces of the boards. The samples used to specify the density profile had the dimensions of 50 x 50 mm and thickness remaining after planing on both sides and were cut from the middle part of the compressed boards.

In order to carry out the densification process in industrial conditions at the Wersal company, a high-pressure press was used, produced by Italpress, model GL/260-PS, which allowed flat compression of boards that were up to 2.5 m long. Before densification, timber, MC, 11.5%, was heated between the press shelves at a temperature of 90 °C, over the course of 20 minutes, in order to soften the lignin, and then it was densified in three steps. In the first step, the timber was flattened from 24 mm to 22 mm (4mm, press shelf move), and the press was opened (the top shelf was moved upwards from the compressed timber piece); in the second pulse, timber was compressed to 20 mm (6 mm press shelf move), and the shelf was opened once again, separating it from the compressed board, to allow for stress relaxation. In the third pulse, the timber was compressed to 18 mm (8 mm press shelf move). In the last pulse of compression, the timber remained closed tightly in the press for 30 seconds, after which the press shelves were opened.

Statistical analysis of the results was carried out using Statistica version 13 (TIBCO Software Inc., CA, USA). The analysis of variance (ANOVA) was used to test ($\alpha = 0.05$) for significant differences between factors. A comparison of the means was performed using Tukey's test, with α=0.05.

3. Results and Discussion

3.1. Density of Wood before and after Thermo-mechanical Densification

A phenomenon of elastic redeformations was observed in the densified boards after each pulse of compression, and after the last pulse, there was a redeformation back to the average thickness of ca. 20 mm. Timber pieces, whose initial nominal thickness amounted to 24 mm, were compressed to 20 mm (CR compression ratio 20%), while the initial board width, 90 mm, increased to 92 mm. The obtained cross-sections of the boards after compression were not flat. As a result of the thermo-mechanical compression, the average timber moisture content dropped to 9% and the average density increased by 13.5%, from of 547 to 621 kg/m^3.

Figure 1 presents the relation between timber density before and after TMD. Both sets have a normal distribution. It has been observed that as a result of thermo-mechanical densification, timber density increased in a statistically significant manner ($p < 0{,}05$), compared to the initial density before TMD. The average density of the entire timber batch (400 pcs.) increased by 14%. The relation between timber density before and after TMD is high (determination coefficient equals 0.78). A high determination coefficient reflects a quite uniform augmentation of the density of individual timber pieces as a result of TMD. Of course, the increase in density of a single piece of timber depended on its initial density. In the case of timber pieces with high initial density (and, at the same time, low porosity), the increase in density caused by thermo-mechanical densification was smaller (Table 1).

The density of wood before and after thermo-mechanical densification, taking into account the results of strength grading before and after thermo-mechanical densification has been presented in Table 1 and Table 2. The results refer to the same batches of boards classified in a given class before densification.

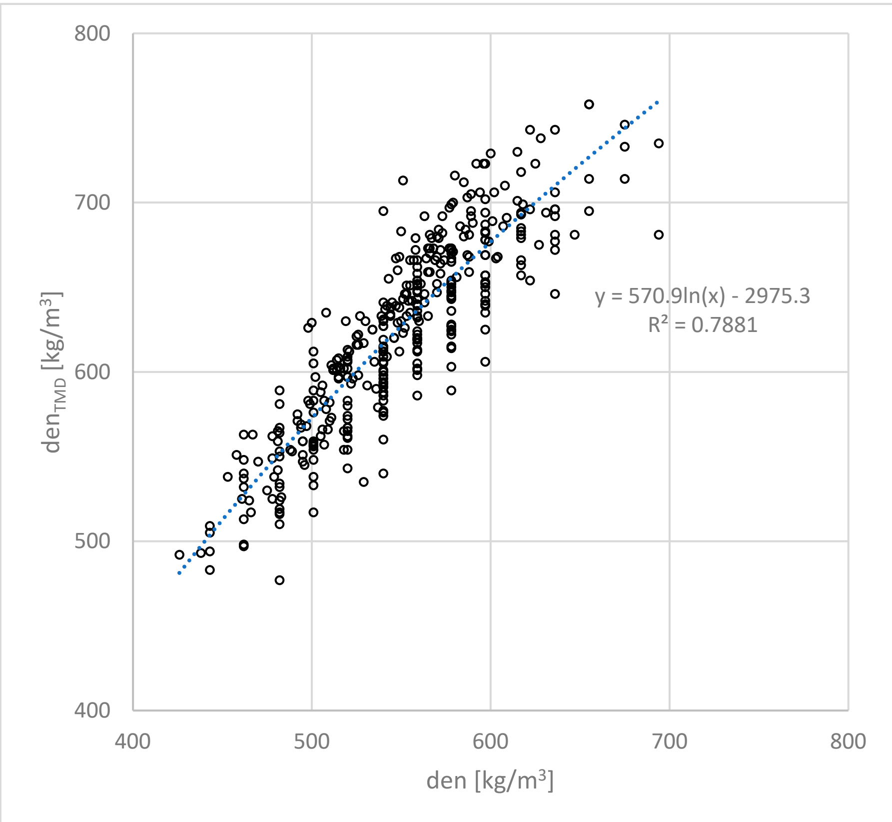

Figure 1. Relation between timber density before and after densification.

Table 1. Timber density before and after thermo-mechanical densification for timber classified in different strength grades before thermo-mechanical densification.

C Class of Graded Sawn Timber Determined before Densification	Average Density before Densification	Average Density after Densification	Density Increase
	[kg/m³]	[kg/m³]	[%]
C18	518 (54)	583 (62)	13
C24	506 (31)	573 (40)	13
C30	559 (25)	639 (33)	14
C35	600 (28)	679 (30)	13
C40	675 (19)	720 (30)	7
ALL	547 (48)	621 (48)	14

Table 2. Timber density after thermo-mechanical densification for timber classified in different strength grades after densification.

C class of Graded Sawn Timber Determined after Densification	Average Density after Densifiction
	[kg/m³]
C18	652
C24	550
C30	586
C35	639
C40	652
ALL	621

By analysing the results presented in Table 1, it can be concluded that the highest density increase took place in the case of boards classified into class C30 after TMD (14.3%), and the smallest in the case of boards classified in the C40 class (6.7%). The density increase for all the boards amounted to 13.5%. In the case of densified timber from class C18, it stands out for its high density in comparison with the remaining C classes of densified timber (Table 2) and is 25.9% higher than the density of C18 timber before thermo-mechanical densification.

Figure 2 presents density distribution curves for the timber under research before and after modification. The curves show the changes in density that happened as a result of thermo-mechanical modification. TMD caused an increase in the density of timber under research by about 14%. Both before and after TMD modification, there is a negative kurtosis, which indicates a left-skewed asymmetry of distribution. The obliqueness, in both cases, is close to zero (distribution similar to a symmetrical one). After the modification, the obliqueness is skewed to the left (domination of lower-density values). The distribution is close to the normal distribution (kurtosis value = 0). Kurtosis is negative, which means there are fewer positive outliers than in a normal distribution.

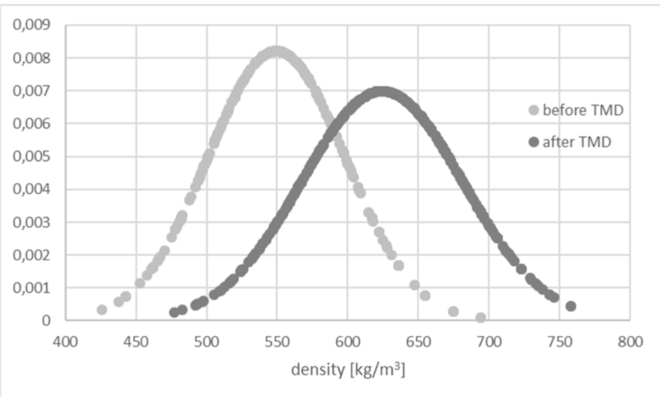

Figure 2. Timber density distribution before and after thermo-mechanical modification.

Examples of density profiles before and after thermo-mechanical densification have been presented in Figure 3 and in Figure 4. The thickness of pieces after TMD for which the density profile has been determined was smaller than the thickness of timber pieces for which strength class was determined, which resulted from their planing in order to achieve flatness. The obtained density profiles confirm that timber has been densified in a uniform manner throughout its entire volume. As a result of the thermo-mechanical densification of pine wood, the differences between earlywood and latewood become smaller. Before thermo-mechanical modification, the density of the entire batch of tested timber was between 426 kg/m^3 and 694 kg/m^3. After thermo-mechanical modification, the density of the tested batch of timber was between 477 kg/m^3 and 758 kg/m^3.

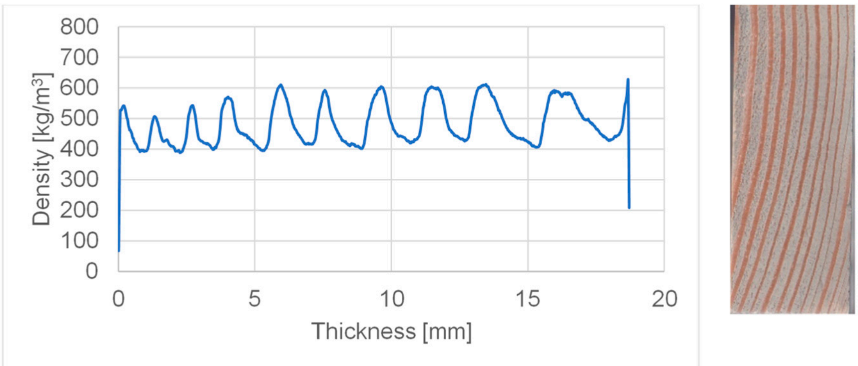

Figure 3. Density profile and cross-section of sawn timber before thermo-mechanical densification, average density of sample 482kg/m^3. Sawn timber samples before modification were planed on both sides to achieve flatness.

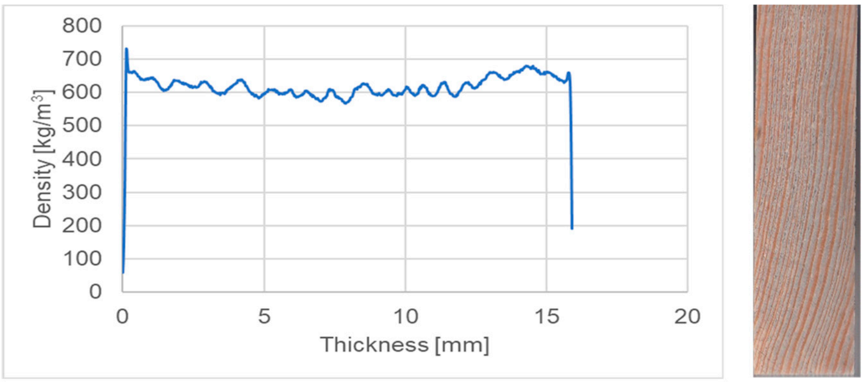

Figure 4. Density profile and cross-section of sawn timber after thermo-mechanical densification, average density of sample 615 kg/m^3. Sawn timber after densification was planed on both sides to achieve flatness.

The thermo-mechanical modification of pine wood influences both its internal structure and its properties. The density profile of pine boards became more homogenous. Before densification, there were visible differences between the density of earlywood and latewood (Figure 3). After the modification, the density of pine wood in the element's thickness became more uniform (Figure 4), and more intense material densification occurred in earlywood areas. The same has also been confirmed by the observations of Nilsson et al. (2011) [41]. This is due to the fact that in coniferous wood, earlywood cells have bigger cross-section dimensions and thinner cell walls than latewood. A similar effect has been reported in the literature in reference to densified spruce wood [13,42,43]. In turn, the way cells are densified has a very significant influence on the mechanical and physical properties of the material under modification [43].

3.2. Dynamic Modulus of Elasticity before and after Thermo-mechanical Densification

The relation between the modulus of elasticity before and after TMD modification, for the entire batch of timber under study, has been presented in Figures 5 and 6. For both sets, departures from normality were observed.

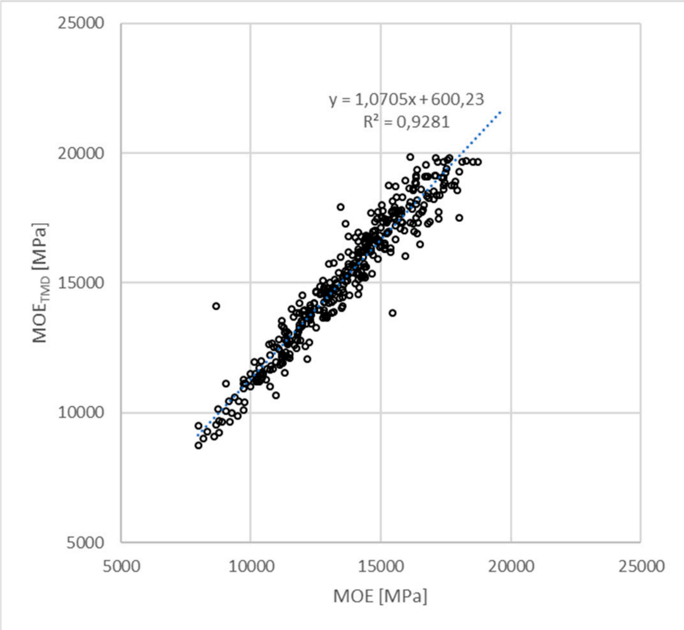

Figure 5. Relation between MOE before and after densification.

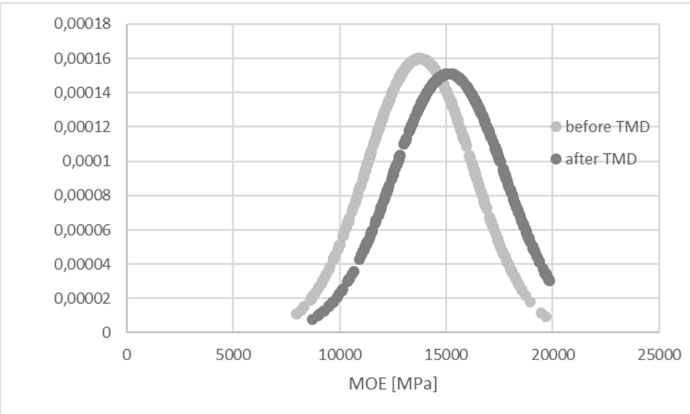

Figure 6. MOE distribution before and after thermo-mechanical modification in the timber under study.

Figure 6 shows an increase in MOE as a result of TMD modification. The main value of MOE incremented by ca. 10%. Both before and after TMD modification, there is a negative kurtosis, which indicates a left-skewed asymmetry of distribution. The obliqueness, in both cases, is close to zero (distribution similar to a symmetrical one). After the modification, the obliqueness is skewed to the left (domination of lower MOE values). The distribution is close to the normal distribution (kurtosis value = 0). Kurtosis is negative, which means there are fewer positive outliers than in a normal distribution.

The dynamic modulus of elasticity of wood (MOE_dyn) before and after thermo-mechanical densification, for the various C classes of strength-graded timber determined before densification, has been presented in Table 3.

By analysing the results presented in Table 3, it can be concluded that the largest increase of MOE_dyn took place in the case of boards classified into the C18 strength grade before densification (13.6%) and the smallest in the case of boards classified as C40 (1.2%). For the remaining classes, the changes in MOE values were the following: C24 (12.1%), C30 (12.0%) and C35 (9.9%). The increase of dynamic modulus of elasticity for all the boards amounted to 11.4%. In the case of the group of boards that, before densification, was classified as C40, the increase of the modulus of elasticity was the smallest. For a part of the boards, 17 pieces, including 4 pieces from the C40 class and 13 pieces from the C35 class (graded before densification), whose density increased, as a result of compression, from 613 kg/m^3 to 705 kg/m^3, we were not able to specify the strength class using the MTG device. C classes and average MOE_dyn board after wood densification are presented in Table 4.

Table 3. Dynamic modulus of elasticity before and after thermo-mechanical densification for timber classified in different strength grades before thermo-mechanical densification.

C Class of Graded Sawn Timber Determined before Densification	Average Dynamic Modulus of Elasticity before Densification	Average Dynamic Modulus of Elasticity after Densification	Modulus of Elasticity Increase
	[MPa]	[MPa]	[%]
C18	8913 (575)	10128 (1179)	14
C24	11626 (990)	13030 (1355)	12
C30	14286 (871)	16000 (1268)	12
C35	16690 (872)	18346 (952)	10
C40	18385 (693)	18602 (1523)	1
ALL	13586 (2495)	15131 (2494)	11

Table 4. Dynamic modulus of elasticity after thermo-mechanical densification for timber classified in different strength grades specified after thermo-mechanical densification.

C Class of Graded Sawn Timber Determined after Densification	Average Dynamic Modulus of Elasticity MOE_dyn after Densification
	[MPa]
C18	9127
C24	11304
C30	13570
C35	16187
C40	18555
ALL	15131

Figure 7 presents the relation between the density and MOE of timber, taking into account the results of strength grading.

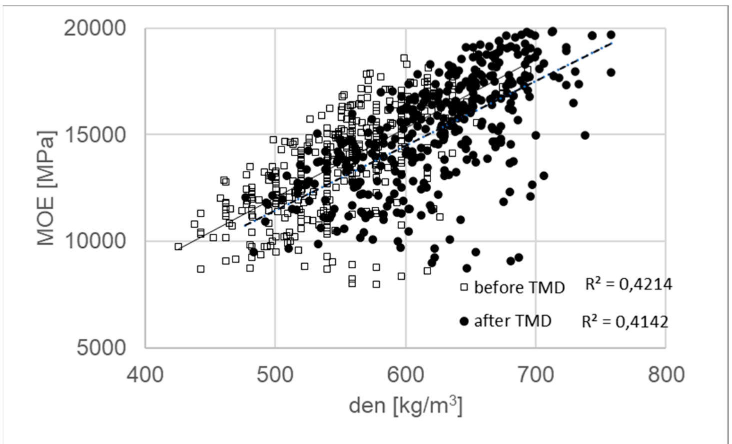

Figure 7. Relation between density and MOE (before and after TMD modification).

3.3. Structure of C Strength Grades before and after Thermo-mechanical Densification

As a result of the thermo-mechanical densification of pine-sawn timber, there have been changes in the structure of share of strength classes in the batch of timber under study (Figure 8). In the case of the set of timber pieces strength graded with the machine method before thermo-mechanical densification, the dominant timber classes were C24 and C30. As a result of thermo-mechanical densification, C35 became the most dominant timber class. The second largest share corresponded to class C30, while C40 came third.

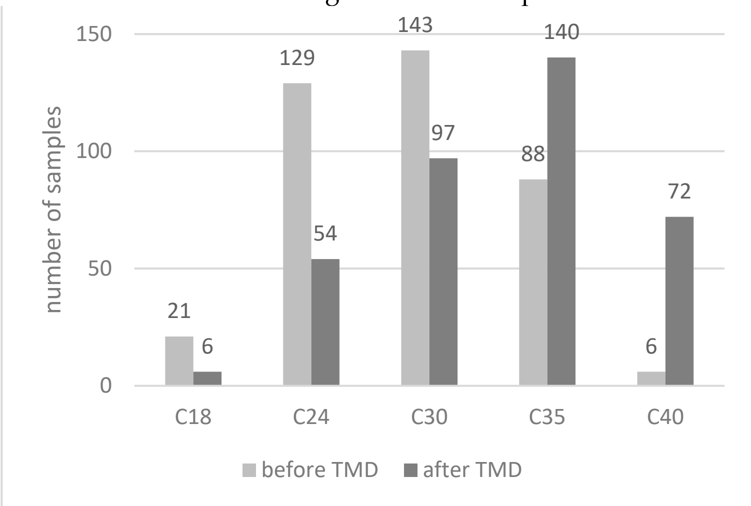

Figure 8. Structure of C classes before and after thermo-mechanical densification.

The obtained results permit us to conclude that, as a result of thermo-mechanical densification of timber, its density grows, which translates, as a consequence, into an increase of the dynamic modulus of elasticity specified with a non-destructive method, using the MTG device (Mobile Timber Grader). The strength grading of timber before and after densification results in a significant increase in the share of pieces in higher C classes.

The effectiveness of board densification (density increase) fell within the range of 8-14%. The highest densification (12%–14%) has been observed for timber from classes C18, C24, C30, and C35. In each case, the observed differences in density values before and after densification were statistically significant (different homogeneous groups in Table 5). In the case of modification of wood from the C40 class, the density increase we observed (8%) was visible but statistically insignificant (the same homogeneous group "f" in Table 5). It is worth noting that the highest percentual influence on material densification (54.1%—Table 6) resulted from the initial class of wood, which depended on the material's initial parameters. Both the densification process itself and the interaction between the densification process and the initial class of timber were characterised by a lower influence on the density increase than other factors that have not been taken into account in the current study (error = 36.2%).

Together with the densification increase, we also observed an increase in MOE for the timber under research. It fell within the range of 9%–14% for timber from classes C18, C24, C30, and C35. In each case, the increase of MOE values was statistically significant (different homogeneous groups in Table 5). The highest improvement of this parameter (14%) was observed for the lowest initial class, C18. In the case of the initial class C40, the modification process did not cause an improvement in MOE values (the same homogeneous group "H" in Table 1). It is worth noting that, similarly to density, the highest percentual influence on MOE values increase (81.5%—Table 6) resulted from the initial class of wood, which depended on the material's initial parameters. Both the densification process itself and the interaction between the densification process and the initial class of timber were characterised by a lower influence on the MOE values increase than other factors that have not been taken into account in the current study (error = 17.5%).

Table 5. Properties (homogeneous groups).

Modification	Class (before densification)	Density [kg/m³]	Homogeneous groups	MOE [MPa]	Homogeneous groups
NM	C18	518	a	8913	A
TMD		583	d,c,d	10128	B
NM	C24	506	a	11626	C
TMD		573	c	13030	D
NM	C30	559	b	14286	E
TMD		639	e	16000	F
NM	C35	599	d	16863	G
TMD		681	f	18346	H
NM	C40	675	e,f	18602	G,H
TMD		727	f	18864	H

NM—not modified; TMD—modified.

Table 6. ANOVA for selected factors affecting density and MOE of tested wood.

Source of variance	Density		MOE	
	p	P (%)	P	P (%)
densification	0.000000	9.2	0.000000	0.7
initial class	0.000000	54.1	0.000000	81.5
Densification x initial class	0.047054	0.5	0.101145	0.2
Error		36.2		17.5

p—probability of error, P—percentage of contribution

4. Conclusions

The thermo-mechanical densification of flatsawn pine timber boards increases the values of its density by 13.5% on average, which translates into the average increase of the dynamic modulus of elasticity by 9% and causes changes in the number of timber pieces classified into the individual C strength grades.

As a result of thermo-mechanical densification in industrial conditions, the strength class C of most Scots pine timber pieces improves. Most timber pieces that were subjected to thermo-mechanical densification have improved their strength class, C, by one (72.7% of the tested batch) or two C classes (3.6% of the batch under study).

Thermo-mechanical densification causes an increase in the quality (expressed by average values of density and dynamic modulus of elasticity) of timber for construction applications.

Author Contributions: Conceptualization, I.B. and S.K.; methodology, I.B. and S.K.; software, I.B. and P.B., validation, I.B. and S.K.; formal analysis, I.B., P.M., P.B. and S.K.; investigation, I.B., P.M. and S.K.; resources, I.B., M.G. and S.K.; data curation, I.B, P.M. and P.B.; writing—original draft preparation, I.B., P.M., M.G., P.B. and S.K.; writing—review and editing, I.B.; visualization, I.B.; supervision, S.K.; project administration, I.B. and S.K.; funding acquisition, S.K. All authors have read and agreed to the published version of the manuscript.

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