Effect of the Layer Structure of Wooden Floorings on Dimensional Mobility under Different Relative Humidity and Water Retention Conditions

Ihsan Kureli
Nihat Dongel

Abstract

This study aimed to determine the effect of different wood flooring layer structures and surface features on water intake, shrinkage, and swelling rates under different relative humidity and water retention conditions. Nine wood flooring sample types were tested: solid wood beech (*Fagus orientalis* L.) flooring covered with polyurethane varnish, four engineered wood flooring types having different core-layers (solid-wood poplar (*Populus nigra* L.), 2× medium-density fiberboard, and plywood) covered with ultraviolet dried polyurethane varnish on beech veneer, and four laminated wood flooring types having different core layers (high-density fiberboard, medium-density fiberboard, particleboard, and plywood). The results showed the lowest water retention increase rates for 2 and 24 hours in the high-density fiberboard and medium-density fiberboard core-layered laminated wood floorings. The lowest thickness swelling rate occurred in the laminated wood flooring with a plywood core layer during exposure to high relative humidity, whereas the lowest swelling rate in the width dimension occurred for laminated wood flooring compared with other product types. The lowest thickness shrinkage rate was in the poplar core-layered engineered wood flooring, whereas the lowest shrinkage rate in the width direction was in the medium-density fiberboard core-layered engineered wood flooring and plywood core-layered laminated wood flooring at lower relative humidities. In conclusion, high-density fiberboard and medium-density fiberboard core-layered laminated wood floorings are advisable for flooring exposed to a humid environment. All laminated wood flooring types provided good resistance to swelling. The plywood core-layered laminated wood floorings, poplar, and medium-density fiberboard core-layered engineered wood flooring types performed the best for low-humidity environments.

Wood floors are structurally manufactured in three groups: solid wood floorings (SWFs), laminated wood floorings (LWFs), and engineered wood floorings (EWFs). SWFs are produced from one piece of wood, whereas LWFs and EWFs are produced from three-layered pieces of wood in which the layers are glued together. In addition, perpendicular massive planks of wood or plywood (planks) are used for the backing and core layers of EWFs, whereas on the surface layers, a solid sawn-wood lamella produced by the sawing technique is used by parallel positioning to the backing layer. LWFs are also three layers and consist of the laminated material on the surface, fiberboard or particleboard in the core, and melamine-impregnated paper as backing.

Wood is a hygroscopic material that takes on moisture from the surrounding environment. Moisture exchange between wood and air depends on the relative humidity, temperature, and wood moisture content (MC). This moisture equilibrium relationship has an important influence on wood properties and performance. Many of the challenges of using wood as an engineering material arise from changes in MC or an abundance of moisture within the wood (Glass and Zelinka 2010). These changes occur only below the fiber saturation point where the removal or addition of water molecules shrinks or swells the wood, respectively (Peng et al. 2016).

Wood shrinking and swelling are inevitable because of the continuous changes of air temperature and relative humidity around the wood floorings during summer and winter. If necessary measures (varnishing, impregnation,

The authors are, respectively, Associate Professor and Associate Professor, Dept. of Wood Products Industrial Engineering, Gazi Univ., Ankara, Turkey (ikureli@gazi.edu.tr [corresponding author], ndongel@gazi.edu.tr). This paper was received for publication in May 2019. Article no. 19-00025.

Forest Prod. J. 70(1):122–133.
doi:10.13073/FPJ-D-19-00025

etc.) are not taken, then this dimensional mobility in wood flooring will cause serious issues for the homeowner. In cases of high humidity, cracks and gaps in the floor can be observed because of rapid and uneven shrinkage that results from interior space heating and a subsequent decrease in relative moisture.

Deformations such as cupping and bowing on the surface layer can be seen in cases of high relative humidity with unstable water intake. If there is water leakage on the floor surface, then the relative humidity is too high, or if the subfloor construction is insufficient, then a complete bowing deformation can occur. The intensity of the problem varies according to factors such as the environmental temperature and relative humidity, the duration of exposure to adverse effects, the structural characteristics of the materials used in production, and the surface processes.

Belt et al. (2013) studied the effect of process parameters on the cupping behavior of surface-densified Scots pinewood. Their results showed that cupping was strongly affected by the process parameters of densification, with the compression ratio being the most influential parameter. Samples with a low compression ratio always cupped on the undensified side and the extent of cupping increased with increased holding time, temperature, and initial MC.

Barbuta et al. (2012a) made an experimental and finite element model study on the determination of the physical and mechanical properties of EWFs. They used oriented strand board (OSB) as a substrate and the effects of density and MC were examined. The results showed that the cupping deformation of EWF was induced by varying the ambient relative humidity from 50 to 20 percent at 20°C. This experimental finding displayed good numerical estimations for the EWF cupping. The levels of interlaminar stresses are maximal near the free edges of the EWF strips.

Kamperidou et al. (2013) subjected poplar (*Populus nigra* L.) wood to thermal treatments at 180°C and 200°C for 2, 4, 6, 8, and 10 hours to investigate the effect of heat treatment on the hygroscopic properties. They pointed out that swelling in a tangential direction decreased within the ranges of 8.17 and 33.3 percent for specimens treated at 180°C and the ranges of 43.85 and 65.09 percent for specimens treated at 200°C for 2 to 10 hours by referring to the final measurement after 72 hours of water immersion. The swelling decrease ranged between 2.47 and 28.45 percent for specimens treated at 180°C and between 19.62 and 60.87 percent for specimens treated at 200°C for 2 to 10 hours, respectively, in a radial direction after 72 hours of immersion. Most of the heat treatments also resulted in an absorption decrease, attesting to the improvement of the poplar wood hygroscopic behavior (Kamperidou et al. 2013); Rahimi et al. (2019) showed a reduction in volumetric shrinkage of the poplar material when exposed to hydrothermal treatments.

Knapic et al. (2012) experimentally assessed dimensional stability to air humidity and liquid water of cork oak wood (*Quercus suber* L.) floor. They stated that the cork oak wood floor had medium movement in service and small swelling in liquid water (2% to 3%).

The effects of Al_2O_3 content in varnish and high variation of MC on the surface were observed for product checking by submitting flooring samples to aging cycles (i.e., simulated alternating summer and winter conditions; Blanchet et al. 2008). The results showed that an increase in wood MC resulted in a lower presence of varnish in the checks, because the swelled fibers kept the varnish at the surface during the varnishing process. More than 80 percent of the checks were initiated at a ray cell or annual ring location and it was an indication that checking was related to wood anatomy as opposed to Al_2O_3 content of varnish.

Bouffard et al. (2010) evaluated the long-term performance of EWF made with a three-layer OSB substrate manufactured with three adhesive configurations. The results of this experimental study indicated no significant difference between the long-term performance of the OSB substrate made with polymeric methyl diphenyl diisocyanate resin and that of the Baltic birch plywood (BBP) substrate (Bouffard et al. 2010). A study by Blanchet et al. (2003) showed that construction made with a white birch (*Betula papyrifera*) core showed a 10 to 40 percent lower cupping distortion than those made with a black spruce (*Picea mariana*) core when exposed to two conditioning cycles. The varnish layer played an important role in the performance of EWF by reducing the cupping distortion by 50 percent, since it limits moisture absorption through the surface layer (Blanchet et al. 2003). The long-term performance of EWF constructed with three substrates (Russian plywood, high-density fiberboard [HDF], and OSB), three surface components (sawn, sliced, and peeled), and four cold-set adhesives (polyvinyl acetate [PVA], epoxy, hot-melt polyurethane, and ethylene propylene) was investigated by Blanchet (2008). These results showed that a Russian plywood substrate provided the best resistance to aging, followed by HDF and then OSB. Sawn surface components developed the most significant aging, more than either the peeled or sliced surface components. All adhesives had similar behavior except for epoxy, which exhibited poor gluing and delamination.

Gu et al. (2005) studied the effect of wood species, resin type, and vertical density profile on the total and layer thickness swell (TS). Results from a small sample of commercial OSB panels indicated that aspen OSB exhibited the lowest total TS among the three commonly used materials for OSB panels (southern yellow pine, aspen and yellow poplar [*Liriodendron tulipifera*]). At water exposure times of 2, 8, 24, and 96 hours, 73, 70, 65, and 55 percent, respectively, of the total TS occurred in the top and bottom face regions, which accounted for less than 50 percent of the panel thickness. Statistically significant linear relationships were found between the edge TS and TS at 1 inch from the edge, which is the standard TS test for each water exposure time.

Bouffard and Blanchet (2009) carried out a study to identify key design parameters in EWF made with medium-density fiberboard (MDF) and HDF substrates by considering the density of the fiberboard, the characteristics of the face layer, and the type of backing process. A sliced face layer led to lower cupping deformation than a sawn face layer. With a sawn face layer, a denser HDF provided a better substrate for EWF. The use of melamine-impregnated paper as a backing layer significantly contributed to reduced cupping deformation in all cases.

In an experimental study carried out by Zivkovic et al. (2008), a hygroscopic range and equilibrium MC at ambient conditions of heat-treated wood of two wood species (ash [*Fraxinus* spp.] and beech [*Fagus orientalis* Lipsky] at 190°C and 210°C) were investigated and the properties were compared with native wood. The results showed that shrinking gradients of heat-treated wood were not reduced in comparison with native beech wood, but the absolute reduction in water uptake resulted in a 50 percent lower equilibrium MC.

Barbuta et al. (2012b) studied the effect of substrate type on the distortion of EWFs. They manufactured EWFs with different structures by using five types of substrate (BBP, sheathing OSB, web stock OSB, and the two specialty OSBs). Their findings concluded that the BBP substrate exhibited the lowest distortion when going from humid to dry conditions. Likewise, they found that flooring with OSB sheathing, OSB web stock, and ponderosa pine (*Pinus ponderosa*) OSB components resulted in higher distortion. The PVA type I adhesive led to a weak bonding with a high-density OSB surface.

Guo et al. (2017) studied the dimensional stability of EWF in heating systems. The results indicated that in length, whatever the structure and decorative veneer of flooring were, the dimensional stability of EWF had a better performance. With the same structure and decorative veneer, the dimensional stability of the EWF with the veneer shape of monoblock was better than the shape of three splices.

In today's environment, wood flooring can be exposed to water and low- or high-humidity conditions as a result of global warming-borne floods, forgotten or obsolete plumbing, water and air conditioning equipment, the use of Turkish or Finnish baths, and use in different climatic zones (tropical or arid), etc. Therefore, research on this subject is important. Considering the number of different floorings and complementary elements that go into the present flooring industrial projects, designers should be aware of the consequences of their work and must begin to consider the impact on application. This article analyzes the effects of different layer structures and different surface features of SWFs, EWFs, and LWFs on the rates of water intake, swelling, and shrinkage under water and different climatization conditions.

Materials and Methods

Materials

Beech.—Beech logs used in the manufacture of surface and backing layers for EWFs and SWFs were chosen from the lumberyard at a factory producing wood floorings in Ankara, Turkey. In the selection of logs, care was taken to ensure that the stem was fully cylindrical and that the annual rings were smooth and that there were no defects such as knots, fiber curls, cracks, etc. The mean diameter of the logs was 300 mm, the mean annual ring width was 0.5 mm, and the mean ovendried mass density was 0.63 g/cm^3.

Poplar.—Poplar logs used in the production of alternative core layers for EWFs were chosen from the lumberyard at a factory in Ankara, Turkey. Care was taken in the selection of the logs to keep the full cylindrical body, uniform annual rings, and the absence of defects such as cracks, knots, fiber curls, etc. The mean diameter of the logs was 350 mm, the mean annual ring width was 5 mm, and the mean mass density was 0.41 g/cm^3.

*Okoume (*Aucoumea klaineana *Pierre)*.—In the backing layer of the EWF, 1-mm-thick Okoume veneer was used as an alternative. Care was taken during veneer selection to ensure the absence of structural and manufacturing defects.

Medium-density fiberboard.—In this study, MDF was used as the core-layer material because it is one of the most used materials in lamination. It had a thickness of 10 mm, dimensions of 280 by 210 cm, and a density of 0.71 g/cm^3. It was manufactured according to the procedures of the TS EN 622-5 standards (Turkish Standards Institution 2011b).

High-density fiberboard.—In this study, HDF was used as the core-layer material because it is one of the most used materials in lamination. It had a thickness of 8 mm, dimensions of 280 by 210 cm, and a density of 0.93 g/cm^3. It was manufactured according to the procedures of the TS EN 316 standards (Turkish Standards Institution 2011a).

Plywood (Beech).—In this study, beech plywood was used as the core-layer material because it is one of the most used materials in lamination. It had a thickness of 8 mm, dimensions of 220 by 170 cm, and a density of 0.63 g/cm^3. It was first-class manufactured according to the procedures of the TS 3103 EN 313-1 standards in an ''enclosed normal air humidity resistant'' environment (Turkish Standards Institution 1998).

Laminate.—Melamine resin and flooring grade standard-featured Çamsan-brand standard high-pressure laminate was used for the surface layer of the laminated floorings with a thickness of 0.6 mm and a weight of 80 g/m^2.

Foil backing layer (direct-pressure laminate).—Melamine resin-impregnated alpha-cellulose–based foil was used for the laminated floorings with a thickness of 0.4 mm and a weight of 120 g/m^2.

Varnish.—The varnish used for varnishing the surfaces of the SWFs and EWFs had a solids content of 40 percent and 50 percent of the two-component polyurethane filler varnish and a finishing varnish.

Adhesive.—Urea formaldehyde adhesive supplied by the Polisan Corporation was used in the layers adhering to each other of the EWF. There were urea resin, formaldehyde, and ammonium chloride as curing agents in their structures. Its density was 1.24 g/cm^3 at 25°C, it had a pH value of 8.1, and a viscosity of 180 cP. It had a solid content of 55 percent and its free formaldehyde content was 0.025 percent. The core layer in the laminated bonding of the surface and backing layers of the solid material and viscosity at the amount of 55 ± 1 percent and 220 cP/25°C PVA-based resin adhesives (Klebond 120) were used.

Preparation of the wood flooring panels

The material, thickness, geometry, and sand arts of the wood flooring panels used in the experiments are shown in Table 1 and Figures 1 through 3. Test panels were manufactured by the manufacturing companies as a plate. Table 1 shows the material, thickness, and geometry design of the wood flooring panels used in the experiments.

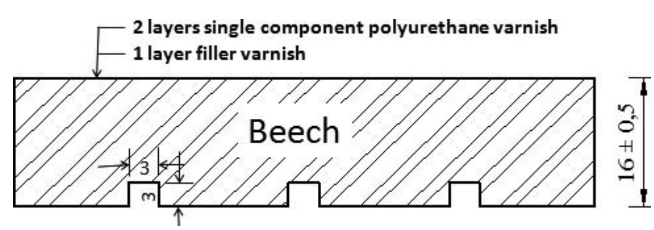

*Figure 1.—Beech (*Fagus orientalis *L.) solid wood flooring samples used in the experiment.*

Table 1.—Material, thickness, and geometrical design of wood flooring panels used in experiments.[a]

Material and standard	Layer thickness (mm)			Geometry of the planks	
	Surface	Core	Backing	Dimension (mm)	No.
EWF (TS 5204 EN 13756)	Beech (4)	Poplar (9.8)	Okoume (1)	1,095 × 180 × 14.8	40
	Beech (1.5)	MDF (10)	Paper (0.5)	1,095 × 180 × 12	40
	Beech (2)	MDF 2 (10)	Beech (2)	1,095 × 180 × 14	40
	Beech (4)	Beech plywood (8)	— (0)	1,095 × 180 × 12	40
LWF (TS EN 438-2)	HPL/FGS (0.6)	HDF (E1 norm) (7)	Balance paper (0.4)	1,295 × 190 × 8	40
	HPL/FGS (0.6)	MDF (7)	Balance paper (0.4)	1,295 × 190 × 8	40
	HPL/FGS (0.6)	Particleboard (7)	Balance paper (0.4)	1,295 × 190 × 8	40
	HPL/FGS (0.6)	Plywood (7)	Balance paper (0.4)	1,295 × 190 × 8	40
SWF (TS EN 13226)		Beech wood (16 ± 0.5)		85 × 250 × 16	40
Total					360

[a] EWF = engineered wood flooring; MDF = medium-density fiberboard; LWF = laminated wood flooring; HPL = high-pressure laminate; FGS = flooring grade standard; HDF = high-density fiberboard; SWF = solid wood flooring.

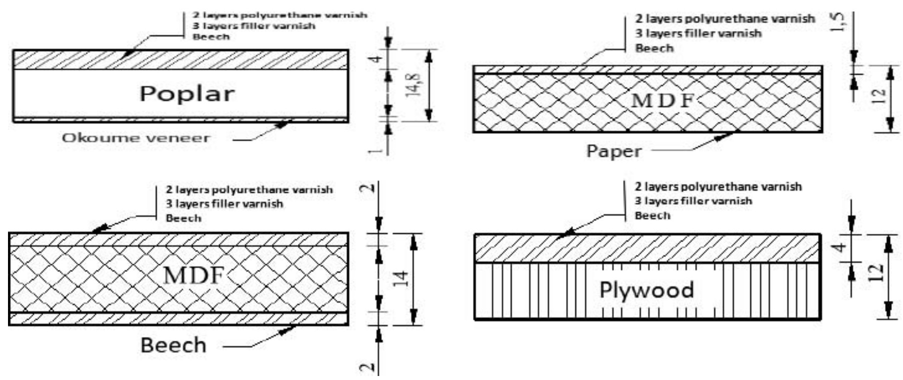

Figure 2.—Layer structure and dimensions (mm) of engineered wood flooring samples. MDF = medium-density fiberboard.

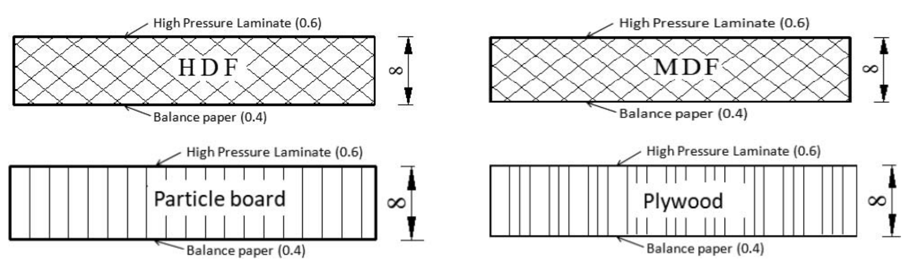

Figure 3.—Layer structure and dimensions (mm) of laminated wood flooring samples. HDF = high-density fiberboard. MDF= medium-density fiberboard.

Preparation of the beech solid-wood panels.—Beech logs were converted to 40-mm-thick lumber in accordance with the parallel and central sawing techniques. The planks of lumber obtained were dried in a kiln to an MC of 9 ± 2 percent. Solid-wood panels based on the general principles envisaged in the TS EN 13226 standards (Turkish Standards Institution 2014) were used from the dried lumber and 80 pieces were produced by using suitable processing techniques in accordance with the parquet form shown in Figure 1.

To ensure samples reached an MC of 9 ± 0.5 percent, SWF samples were immersed in a ''Şimşek'' (Lightning)-brand climate cabin with a temperature of 23°C ± 2°C and relative humidity of 50 ± 5 percent. After conditioning the samples, they were first sanded with an 80-grit and then with a 100-grit sandpaper by using the Makita-brand vibrating hand sanding machine. After vacuum-cleaning the sanded powders with a vacuum cleaner in accordance with the ASTM-D3023 (American Society for Testing and Materials 1998) principles and manufacturer's recommendations, two layers of topcoat polyurethane varnish were applied with a spray gun on the single-layer filler.

Preparation of the EWF panels.—Four different EWFs were used in the experiments, with the dimensions given in Table 1. These were manufactured at a flooring factory according to the structure and number of layers shown in Figure 2. Bonding of the layers to one another was made at a pressing temperature of 110°C, a pressing time of 4 minutes, and a pressure of 6 N/mm^2. Production was made of the finished EWFs to the third-floor filler and two to five coats of polyurethane varnish topcoat were applied. The spray gun varnishing process was applied at 250 g/m^2.

Preparation of the laminated flooring panels.—The dimensions of the panels produced for the laminated flooring samples are given in Table 1 and the layer structure is given in Figure 3.

Preparation of the test specimens.—The TS EN 326 (Turkish Standards Institution 1999d) standards and other standards were used to prepare the test samples. The size and number of samples, which took primary implementation, are given in Table 2.

Methods

Determination of the moisture content.—The TS EN 322 (Turkish Standards Institution 1999b) and TS 2471 (Turkish Standards Institution 2005a) standards were used for the determination of the in the EWF and LWF. The moisture weights (m_{wet}) of the samples were weighed on a ±0.01-g precision analytical balance for this purpose. Subsequently, the samples were dried in a ventilated oven at 103°C ± 2°C until reaching an invariable weight. The samples were then taken from the oven and, after cooling in a desiccator, the ovendried weights (m_{dry}) were determined. On the basis of these procedures, the mMC was calculated using the following equation:

$$\mathrm{MC} = \frac{m_{wet} - m_{dry}}{m_{dry}}(100) \tag{1}$$

Here m_{wet} is the mass of the specimen at a given MC and m_{dry} is the mass of the ovendried specimen.

Determination of the density.—The EWF and LWF samples were determined on the basis of the TS EN 323/1 standards (Turkish Standards Institution 1999c) and the TS 2472 massive samples standards (Turkish Standards Institution 2005b). The samples came to a 9 ± 0.5 percent MC, a 23°C ± 2°C temperature, and a 50 ± 5 percent relative moisture in the air-conditioning cabinets until they reached an invariant mass. The sample density of the mass was calculated with an accuracy of ±0.01 g on the precision balance and with an accuracy of ±0.01 mm for the dimensions with a caliper by using the following equation:

$$\delta = \frac{m}{V} \tag{2}$$

where δ is density (g/mm^3), m is mass (g), and V is volume (mm^3).

Determination of increase in weight, thickness, and width and amount of water intake by holding in water.—The amount of weight increase in the samples by holding in water was made on the basis of the TS EN 317 standards (Turkish Standards Institution 1999a) for the determination of the increase in thickness and width. For this purpose, the samples were kept in an air-conditioning cabinet with a 50 ± 5 percent relative moisture and 23°C ± 2°C temperature until they reached a 9 ± 0.5 percent MC and an equilibrium mass. The mass was determined with a ±0.01-g scale of precision and dimensions with a ±0.01-mm precision caliper. Subsequently, the samples were placed into a vessel filled with the Abant-brand clean water at a pH of 7.57 and a temperature of 20°C ± 1°C so that the surface could be placed at 25 ± 5 mm below the water mark. After 2 and 24 hours, samples were removed and the water deposits ran onto cloth surfaces. Thickness, width, and weight increase rates were

Table 2.—Design of the preparation of test samples.[a]

Flooring type and core layer	Dimension (mm)	Standard	No.
Moisture content samples			
EWF			
Poplar	50 × 50 × 14	TS EN 322	10
MDF	50 × 50 × 12	TS EN 322	10
MDF 2	50 × 50 × 14	TS EN 322	10
Plywood	50 × 50 × 12	TS EN 322	10
LWF			
HDF	50 × 50 × 8	TS EN 322	10
MDF	50 × 50 × 8	TS EN 322	10
Particleboard	50 × 50 × 8	TS EN 322	10
Plywood	50 × 50 × 8	TS EN 322	10
SWF			
Beech	20 × 20 × 15	TS 2471	10
Total			90
Density samples			
EWF			
Poplar	50 × 50 × 14	TS EN 323/1	10
MDF	50 × 50 × 12	TS EN 323/1	10
MDF 2	50 × 50 × 14	TS EN 323/1	10
Plywood	50 × 50 × 12	TS EN 323/1	10
LWF			
HDF	50 × 50 × 8	TS EN 323/1	10
MDF	50 × 50 × 8	TS EN 323/1	10
Particleboard	50 × 50 × 8	TS EN 323/1	10
Plywood	50 × 50 × 8	TS EN 323/1	10
SWF			
Beech	30 × 15 × 15	TS 2472	10
Total			90
Water absorption samples			
EWF			
Poplar	50 × 50 × 14	TS EN 317	10
MDF	50 × 50 × 12	TS EN 317	10
MDF 2	50 × 50 × 14	TS EN 317	10
Plywood	50 × 50 × 12	TS EN 317	10
LWF			
HDF	50 × 50 × 8	TS EN 317	10
MDF	50 × 50 × 8	TS EN 317	10
Particleboard	50 × 50 × 8	TS EN 317	10
Plywood	50 × 50 × 8	TS EN 317	10
SWF			
Beech	50 × 50 × 16	TS EN 317	10
Total			90
Swelling and shrinkage			
EWF			
Poplar	200 × 20 × 14	TS EN 318	5+5
MDF	200 × 20 × 12	TS EN 318	5+5
MDF 2	200 × 20 × 14	TS EN 318	5+5
Plywood	200 × 20 × 12	TS EN 318	5+5
LWF			
HDF	200 × 20 × 8	TS EN 318	5+5
MDF	200 × 20 × 8	TS EN 318	5+5
Particleboard	200 × 20 × 8	TS EN 318	5+5
Plywood	200 × 20 × 8	TS EN 318	5+5
SWF			
Beech	200 × 20 × 16	TS EN 318	5+5
Total			90

[a] EWF = engineered wood flooring; MDF = medium-density fiberboard; LWF = laminated wood flooring; HDF = high-density fiberboard; SWF = solid wood flooring.

measured again and were determined by the following equations:

$$a_t = \frac{t_2 - t_1}{t_1} \times 100 \quad (3)$$

where t_1 is the first measured thickness (mm), t_2 is the thickness after soaking in water (mm), and a_t is the thickness increase rate (%);

$$a_w = \frac{w_2 - w_1}{w_1} \times 100 \quad (4)$$

where w_1 is the first measured width (mm), w_2 is the width after soaking in water (mm), and a_w is the width increase rate (%); and

$$a_m = \frac{m_2 - m_1}{m_1} \times 100 \quad (5)$$

where m_1 is the first weight (g), m_2 is the weight after soaking in water (g), and a_m is the weight increase rate (%).

Determination of dimension changes according to relative humidity variability.—We followed the TS EN 318 standards (Turkish Standards Institution 2005c) to determine the effect of relative humidity on shrinkage and swelling. The samples were kept in an air-conditioning cabinet at a temperature of 20°C ± 2°C and a relative humidity of 65 ± 5 percent until they reached an MC of 9 ± 0.5 percent and a constant mass. The mass was determined with a ±0.01-g precision scale and ±0.01-mm precision caliper. Next, the air-conditioning cabinet temperature remained at 20°C ± 2°C and the constant relative moisture of the environment was maintained separately at 35 ± 5 percent and 85 ± 5 percent adjusted; the samples were kept under these conditions until they reached an unchanging weight. The repeat swelling (α) and shrinkage (β) rates of mass and size measurements were determined with the following equations:

$$\alpha_t = \frac{t_{85} - t_{65}}{t_{65}} \times 100 \quad (6)$$

$$\alpha_w = \frac{w_{85} - w_{65}}{w_{65}} \times 100 \quad (7)$$

$$\beta_t = \frac{t_{35} - t_{65}}{t_{65}} \times 100 \quad (8)$$

$$\beta_w = \frac{w_{35} - w_{65}}{w_{65}} \times 100 \quad (9)$$

Data analysis.—The multivariate analysis of variance was used for the tests of structural differences, depending on the value obtained as a result of wood flooring in determining the effect on the dependent variables, such as density, shrinkage, swelling, and increase rates. The variables were divided into homogeneous groups for the comparison of the difference between the mean values with the Duncan test and the least significant difference based on the critical value. The MSTAT-C software package program was used to analyze the data.

Results and Discussion

Density.—Density values of the test samples are given in Table 3. The highest density was obtained in the HDF LWFs and the lowest was obtained in the poplar EWFs. The HDF substrate LWFs had the highest density (0.891 g/cm^3), whereas the lowest density emerged in the substrate poplar EWFs (0.424 g/cm^3). EWFs and LWFs have multilayer structures. Bonding with adhesives of the high-density middle layer to the upper and lower layers causes even higher overall density. The density is higher in the HDF and MDF in the relatively higher concentration of floorings, which is used as the core of this material.

Table 3.—Density values with air conditioner (23°C ± 2°C; 50% ± 5%)

Flooring type and core layer[a]	Density (g/cm^3), mean (SD)
EWF	
Poplar	0.424[b] (0.021)
MDF	0.787 (0.005)
MDF 2	0.761 (0.004)
Plywood	0.772 (0.009)
LWF	
HDF	0.891[c] (0.005)
MDF	0.842 (0.007)
Particleboard	0.815 (0.018)
Plywood	0.771 (0.015)
SWF	
Beech	0.711 (0.049)

[a] EWF = engineered wood flooring; MDF = medium-density fiberboard; LWF = laminated wood flooring; HDF = high-density fiberboard; SWF = solid wood flooring.
[b] Lowest density.
[c] Highest density.

Amount of thickness, width, and weight increase by holding in water.—Experimental values of the weight, thickness, and width increase quantities of the samples depending on the water intake period (2 and 24 h) are given in Table 4. According to this, there were differences in the amount of water intake depending on the waiting time of the samples in water.

Amount of dimension changes according to relative humidity.—The values of increase and decrease in thickness and width of the test samples are given in Table 5. According to Table 5, an increase in the thickness and width direction compared with that of the material types and values in the direction of reduction in thickness and width were also different.

The wood flooring types, the core-layer material types, the holding time in water and climatic conditions (independent variables), density, water intake rate, and increase in thickness and width (dependent variables) on the analyses of variance to determine whether it is effective were found to be effective on all dependent variables as singles and groups, because the P values were less than 0.05 for all independent variables. It is important to determine whether there are differences between the values of the dependent variables and the results of the Duncan test for grading these values. They have been given separately below.

Weight increase after soaking in water.—The water intake rates depending on the waiting time in water and homogeneity groups based on statistical analysis are given in Table 6 and Figure 4. As can be seen, the water intake amount of the samples at 24 hours was higher than at 2 hours.

Table 4.—Amount of water intake, increase in weight, thickness, and width (%) for time (2 and 24 h) depending on type of wood flooring and core-layer material. Water is potable, 20°C ± 1°C, pH 7.57.

Flooring type and core layer	2 h, mean (SD)	24 h, mean (SD)
Increase in weight (%)[a]		
EWF		
Poplar	23.140 (8.710)	47.830 (7.795)
MDF	5.021 (0.372)	32.260 (6.252)
MDF 2	5.741 (0.592)	20.540 (1.993)
Plywood	15.300 (4.582)	32.670 (5.456)
LWF		
HDF	2.494 (0.144)	11.190 (0.578)
MDF	2.610 (0.219)	11.270 (0.590)
Particleboard	45.040 (2.434)	59.770 (2.171)
Plywood	10.960 (1.975)	28.540 (3.167)
SWF		
Beech	9.888 (0.802)	29.900 (3.157)
Increase in thickness (%)		
EWF		
Poplar	2.830 (1.688)	6.086 (1.633)
MDF	1.103 (0.180)	3.734 (0.454)
MDF 2	1.054 (0.169)	2.913 (0.435)
Plywood	1.494 (0.525)	6.066 (1.529)
LWF		
HDF	0.024 (0.050)	0.444 (0.081)
MDF	0.286 (0.145)	0.843 (0.201)
Particleboard	17.515 (0.804)	23.780 (1.010)
Plywood	0.702 (0.485)	7.018 (1.470)
SWF		
Beech	1.081 (0.501)	3.087 (0.699)
Increase in width (%)		
EWF		
Poplar	0.741 (0.306)	1.374 (0.223)
MDF	0.258 (0.077)	0.930 (0.238)
MDF 2	0.401 (0.084)	0.954 (0.130)
Plywood	0.507 (0.176)	1.431 (0.222)
LWF		
HDF	0.109 (0.027)	0.362 (0.038)
MDF	0.116 (0.015)	0.320 (0.032)
Particleboard	0.916 (0.059)	1.111 (0.059)
Plywood	0.444 (0.098)	0.637 (0.073)
SWF		
Beech	0.965 (0.163)	5.852 (0.630)

[a] EWF = engineered wood flooring; MDF = medium-density fiberboard; LWF = laminated wood flooring; HDF = high-density fiberboard; SWF = solid wood flooring.

Wood flooring type, material type of the core-layer, weight increase rates depending on the waiting time in water, and homogeneity groups based on statistical analysis are given in Table 7 and Figure 5. As can be seen, the lowest weight increase rate by keeping the samples in water for 2 hours was seen in the HDF and MDF core-layered LWFs (2.494% and 2.61%), with the difference between them being insignificant and the highest weight increase rate (45.04%) seen in particleboard LWFs.

The results were similar when the samples were kept in water for 24 hours. The lowest weight increase rate was seen in the HDF and MDF core-layered LWFs (11.19% and 11.27%), whereas the highest weight increase rate (59.77%) was also seen in particleboard LWFs. There was no change in the order of the waiting times in water.

HDF and MDF are produced by mixing very small wood fibers with resin and pressing them under high temperature and pressure. The size of the fibers is very small and compression with high pressure reduces the volumetric void ratio. The small number of voids and the fact that the fibers are completely covered with resin can also be effective in reducing the water intake of the parcels used as the middle layer of these materials. Larger voids resulting from the use of larger particle chips compared with fiberboard and deterioration of structural integrity due to volumetric expansion along with volume expansion and breaking of interparticulate bonds may be the main reasons for more water ingestion.

Thickness increase after soaking in water.—Thickness increase rates and homogeneity groups depending on the core-layer material and water retention time are given in Table 7 and Figure 5. As can be seen, the thickness increase of the samples at 24 hours was found to be higher than at 2 hours.

Weight, thickness, and width increase rates depending on wood flooring type, core-layer material type, and water retention time and homogeneity groups are given in Table 7 and Figure 5. As can be seen, the lowest thickness increase rate (0.02%) was found in the HDF core-layered LWFs, followed by the MDF core-layered LWFs (0.29%) as the samples were kept in water for 2 hours. The highest thickness increase rate (17.51%) was seen in the particleboard LWFs. The results were similar when the samples were kept in water for 24 hours. The lowest thickness increase rates (0.44% and 0.84%) were seen in the HDF and MDF core-layered LWFs, whereas the highest thickness increase rate (23.78%) was also found in the particleboard core-layered LWFs. There was no change in the order of the waiting time in water.

The increase in thickness was directly related to the water intake rate. Fibrous swelling in the cell walls occurred because of the water content of the wooden material up to the degree of moisture saturation. This caused the wooden material to expand in volume. Since the lowest water intake rates were in the HDF and MDF core-layered LWFs, the least increase was in these wood floorings. The high rate of increase in the particleboard core-layered materials is also due to this association.

Width increase after soaking in water.—Width increase rates and homogeneity groups depending on the core-layer material and water retention time are given in Table 7 and Figure 5. As can be seen, the increase in width of the samples in 24 hours was found to be higher than in 2 hours.

The width increase rates and homogeneity groups due to the flooring types, the core- layer type of materials, and the retention time in water are given in Table 7 and Figure 5. As can be seen, the lowest width increase rate (0.11% and 0.12%) was observed in the HDF and MDF core-layered LWFs, whereas the difference between them was insignificant. This was followed by the MDF core-layered EWFs (0.25%). The highest rate of increase in width (0.97%) was seen in the solid beech floorings. The results were similar when the samples were kept in water for 24 hours. The lowest thickness increase rates (0.32% and 0.36%) were found in the MDF and HDF core-layered LWFs, whereas the highest increase rate (5.85%) was found in the solid beech floorings. There was no change in the order of waiting times in water. HDF and MDF were related to the

Table 5.—Values of increase and decrease in thickness and width with increasing (65% to 85%) and decreasing (65% to 35%) relative humidity conditions at 20°C ± 2°C.

Flooring type and core layer[a]	Relative humidity from 65% to 85%		Relative humidity from 65% to 35%	
	% swelling in thickness, mean (SD)	% swelling in width, mean (SD)	% shrinkage in thickness, mean (SD)	% shrinkage in width, mean (SD)
EWF				
Poplar	2.318 (0.290)	0.564 (0.086)	1.050 (0.175)	0.115 (0.042)
MDF	3.812 (0.124)	0.540 (0.014)	1.492 (0.082)	0.362 (0.009)
MDF 2	5.863 (0.311)	0.972 (0.056)	1.159 (0.146)	0.092 (0.013)
Plywood	3.048 (0.398)	0.982 (0.055)	1.254 (0.181)	0.376 (0.044)
LWF				
HDF	3.289 (0.184)	0.172 (0.038)	1.355 (0.124)	0.153 (0.007)
MDF	3.738 (0.190)	0.149 (0.039)	1.185 (0.091)	0.140 (0.015)
Particleboard	3.241 (0.162)	0.202 (0.029)	1.545 (0.159)	0.145 (0.008)
Plywood	2.003 (0.086)	0.146 (0.012)	1.225 (0.083)	0.108 (0.020)
SWF				
Beech	2.365 (0.369)	3.243 (0.247)	1.224 (0.183)	1.308 (0.082)

[a] EWF = engineered wood flooring; MDF = medium-density fiberboard; LWF = laminated wood flooring; HDF = high-density fiberboard; SWF = solid wood flooring.

rate of water intake as well as to the increase in thickness, which is why the core layer has the lowest width increase rate and the solid beech has the highest width increase rate. Unlike the rate of increase in thickness, wood can have a higher increase ratio in a tangential direction, and the increase in width in the solid beech wood floorings may be the reason for it being higher in the particleboard than in the core layer.

Swelling change rates in thickness and width according to relative humidity increase.—In the case of increasing the relative humidity from 65 to 85 percent at an environmental temperature of 20°C, the flooring types, core-layer material types, directional swelling rates, and homogeneity groups are given in Table 8 and Figure 6. The lowest thickness swelling rate (2.00%) occurred in the plywood core-layered LWFs by increasing the relative humidity

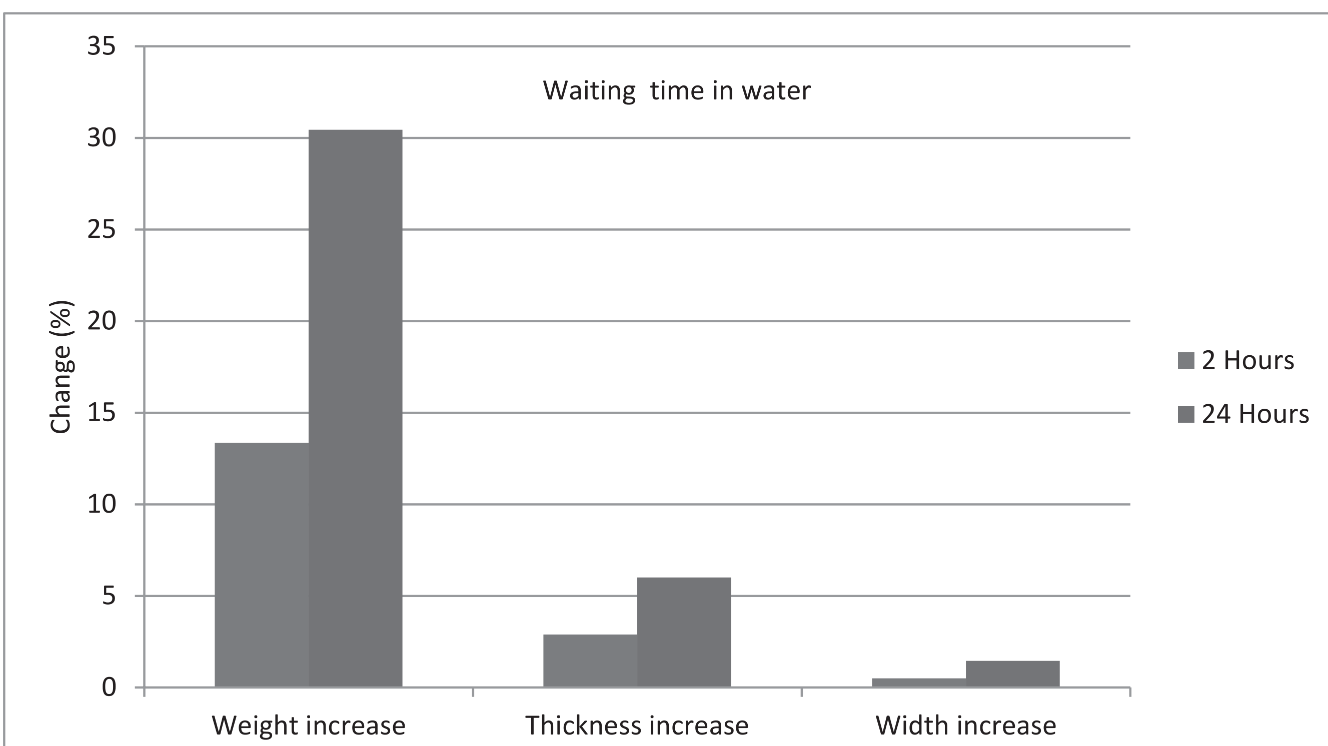

Figure 4.—Amount of weight, thickness, and width increase depending on the waiting time in water.

Table 6.—Weight, thickness, and width increase rates depending on the waiting time in water and homogeneity groups based on statistical analysis.[a]

Increase	Waiting time in water 2 h: mean, HG	24 h: mean, HG	LSD
% weight	13.355, B*	30.441, A**	± 1,134
% thickness	2.898, B*	5.997, A**	± 0.2522
% width	0.495, B*	1.441, A**	± 0.06029

[a] LSD = least significant difference; HG = homogeneity group, statistically significant difference (from A** = maximum [worst] to N* = minimum [best]).

from 65 to 85 percent. The highest thickness swelling rate (5.86%) was determined in the MDF2 core-layered EWFs. The lowest width swelling rates (0.15%, 0.15%, 0.17%, and 0.20%) were found to be negligible in the plywood, MDF, HDF, and particleboard core-layered LWFs, respectively, whereas the highest width swelling rate (3.24%) was observed in the solid beech wood floorings.

SWFs, in the environment in which they are used, absorb or desorb water from the body to reach equilibrium for MC depending on the temperature and relative humidity of the air. Two main mechanisms, surface diffusion and vapor diffusion, are effective in this water movement. By increasing the relative humidity of the air, the water molecules absorbed by the outer and inner surfaces of the parcels move from the wet areas to the dry areas by diffusion. In case of steam diffusion, water movement is from areas with high vapor pressure toward areas with low vapor pressure. Increased temperature and relative humidity increase vapor pressure. The mechanisms are reversible when the temperature and relative humidity drop (Blanchet et al. 2008).

The expansion, contraction, and deformations in the wood floorings are due to the structural features of the wood as well as these mechanisms. The volume of cell wall components (cellulose, hemicellulose, and lignin) decreases and the void volume rate increases by decreasing the density. As the moisture in the circulating air is absorbed by the cell wall components, the expansion decreases as the intensity decreases with the decrease in the intensity of the water. It is possible that the thickness expansion is less in plywood and poplar middle-tiered wood floorings and massive floorings.

In the use of a waterproof laminated material in the upper layer, water diffusion by only the circulating air and the lateral expansion of this material may be the reason for the lower width expansion in the LWFs.

Shrinkage rates in thickness and width in relation to relative humidity decrease.—In the case of decreasing the relative humidity from 65 to 35 percent at an environmental temperature of 20°C, the wood flooring types, core-layer material types, directional shrinkage rates, and homogeneity groups are given in Table 8 and Figure 6. The lowest thickness shrinkage rate (1.05%) was found in the poplar core-layered EWFs. The highest thickness shrinkage rates (1.49% and 1.55%) were found in the MDF core-layered EWFs and in the particleboard core-layered LWFs, respectively, with the difference between them being insignificant. The lowest width shrinkage rates (0.09% and 0.11%) were found in the MDF2 core-layered

Table 7.—Weight, thickness, and width increase rates depending on flooring types, material types of the core layer, and waiting time in water, and homogeneity groups based on statistical analysis.[a]

Flooring type and core layer	Waiting time in water 2 h: %, HG	24 h: %, HG
Weight increase		
EWF		
Poplar	23.140, B	47.830, B
MDF	5.021, E	32.260, C
MDF 2	5.741, E	20.540, E
Plywood	15.300, C	32.670, C
LWF		
HDF	2.494, F*	11.190, F*
MDF	2.610, F*	11.270, F*
Particleboard	45.040, A**	59.770, A**
Plywood	10.960, D	28.540, D
SWF		
Beech	9.888, D	29.900, D
LSD	± 2.101	± 2.097
Thickness increase		
EWF		
Poplar	2.830, B	6.086, C
MDF	1.103, D	3.734, D
MDF 2	1.054, D	2.913, E
Plywood	1.494, C	6.066, C
LWF		
HDF	0.024, F*	0.444, G*
MDF	0.286, F*	0.843, F*
Particleboard	17.515, A**	23.780, A**
Plywood	0.702, E	7.018, B
SWF		
Beech	1.081, D	3.087, E
LSD	± 0.323	± 0.287
Width increase		
EWF		
Poplar	0.741, B	1.374, B
MDF	0.258, E	0.930, D
MDF 2	0.401, D	0.954, D
Plywood	0.507, C	1.431, B
LWF		
HDF	0.109, F*	0.362, F*
MDF	0.116, F*	0.320, F*
Particleboard	0.916, A**	1.111, C
Plywood	0.444, D	0.637, E
SWF		
Beech	0.965, A**	5.852, A**
LSD	± 0.056	± 0.127

[a] HG = homogeneity group, statistically significant difference (from A** = maximum [worst] to N* = minimum [best]). Similar letters indicate that there is no statistical difference. EWF = engineered wood flooring; MDF = medium-density fiberboard; LWF = laminated wood flooring; HDF = high-density fiberboard; SWF = solid wood flooring; LSD = least significant difference.

EWFs and the plywood core-layered LWFs, respectively, with the difference between them being insignificant. It was followed by the poplar core-layered EWFs (0.12%). The highest width shrinkage rates (0.36% and 0.38%) were observed in the MDF and plywood core-layered EWFs, respectively, with the difference between them being insignificant.

When the data of the study were evaluated in general, it was seen that the shrinkage and swelling rates of wooden

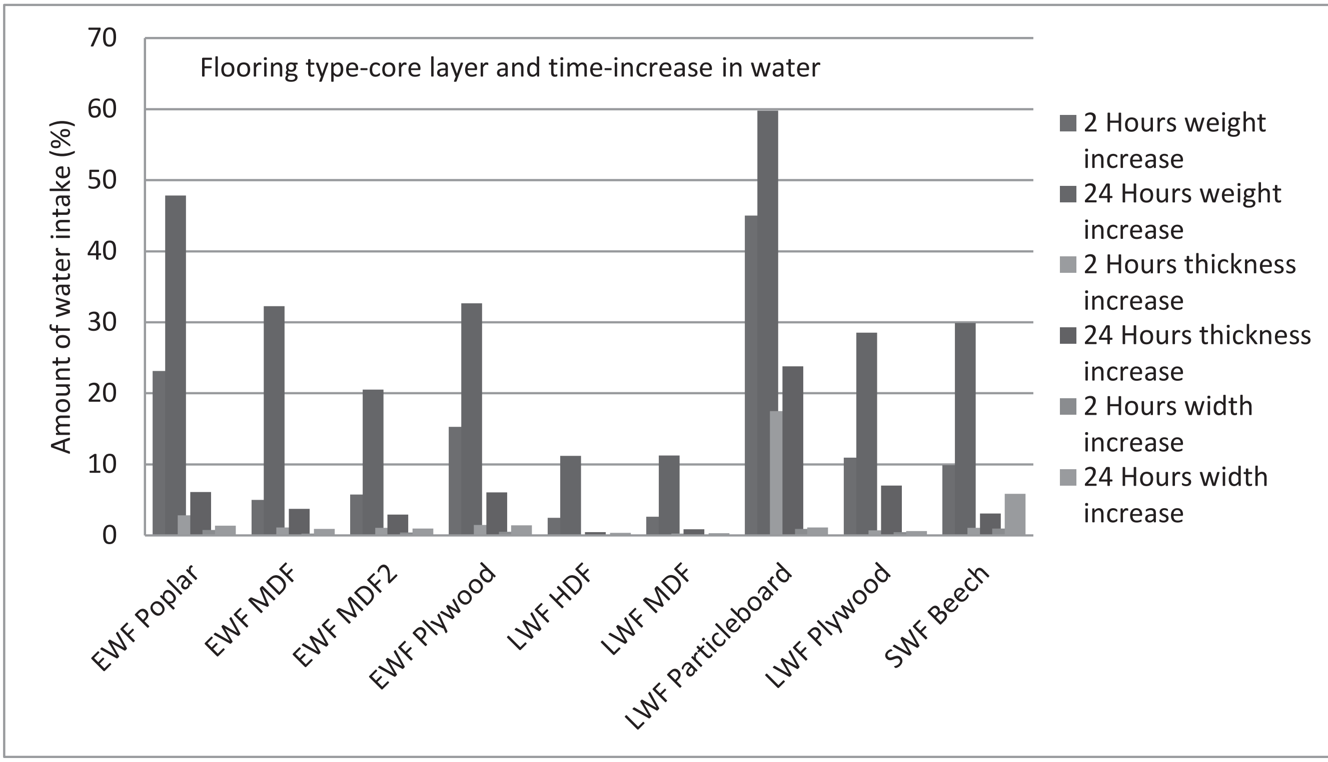

Figure 5.—Amount of weight, thickness, and width increase in different flooring type–core-layer conditions depending on the waiting time in water. EWF = engineered wood flooring; HDF = high-density fiberboard; LWF = laminated wood flooring; MDF = medium-density fiberboard; SWF = solid wood flooring.

Table 8.—Direction-dependent swelling and shrinkage rates depending on wood flooring and core-layer material types in air-conditioning and homogeneity groups based on statistical analysis.[a]

Flooring type and core layer	Increase in relative humidity from 65% to 85% at 20°C		Decrease in relative humidity from 65% to 35% at 20°C	
	% swelling in thickness, HG	% swelling in width, HG	% shrinkage in thickness, HG	% shrinkage in width, HG
EWF				
Poplar	2.318, D	0.564, C	1.050, C*	0.115, DE
MDF	3.812, B	0.540, C	1.492, A**	0.362, B
MDF 2	5.863, A**	0.972, B	1.159, BC	0.092, E*
Plywood	3.048, C	0.982, B	1.254, BC	0.376, B
LWF				
HDF	3.289, C	0.172, D*	1.355, AB	0.153, C
MDF	3.738, B	0.149, D*	1.185, BC	0.140, CD
Particleboard	3.241, C	0.202, D*	1.545, A**	0.145, C
Plywood	2.003, E*	0.146, D*	1.225, BC	0.108, E*
SWF				
Beech	2.365, D	3.243, A**	1.224, BC	1.308, A**
LSD	± 0.3026	± 0.07435	± 0.1885	± 0.02810

[a] HG = homogeneity group, statistically significant difference (from A** = maximum [worst] to N* = minimum [best]). Similar letters indicate that there is no statistical difference. EWF = engineered wood flooring; MDF = medium-density fiberboard; LWF = laminated wood flooring; HDF = high-density fiberboard; SWF = solid wood flooring; LSD = least significant difference.

floorings in water and under different relative humidity conditions differ according to the structural materials used. Densification (Belt et al. 2013) and heat treatment (Zivkovic et al. 2008, Kamperidou et al. 2013) or varnish (Blanchet et al. 2003, 2008) can be applied to the top layer of the wood floorings to reduce dimensional mobility due to shrinking and swelling resulting from water exchange, or a waterproof material such as laminates may be used as the face or back layer (Bouffard and Blanchet 2009).

Additions to the results obtained will be useful for manufacturers, designers, and users under the topics of

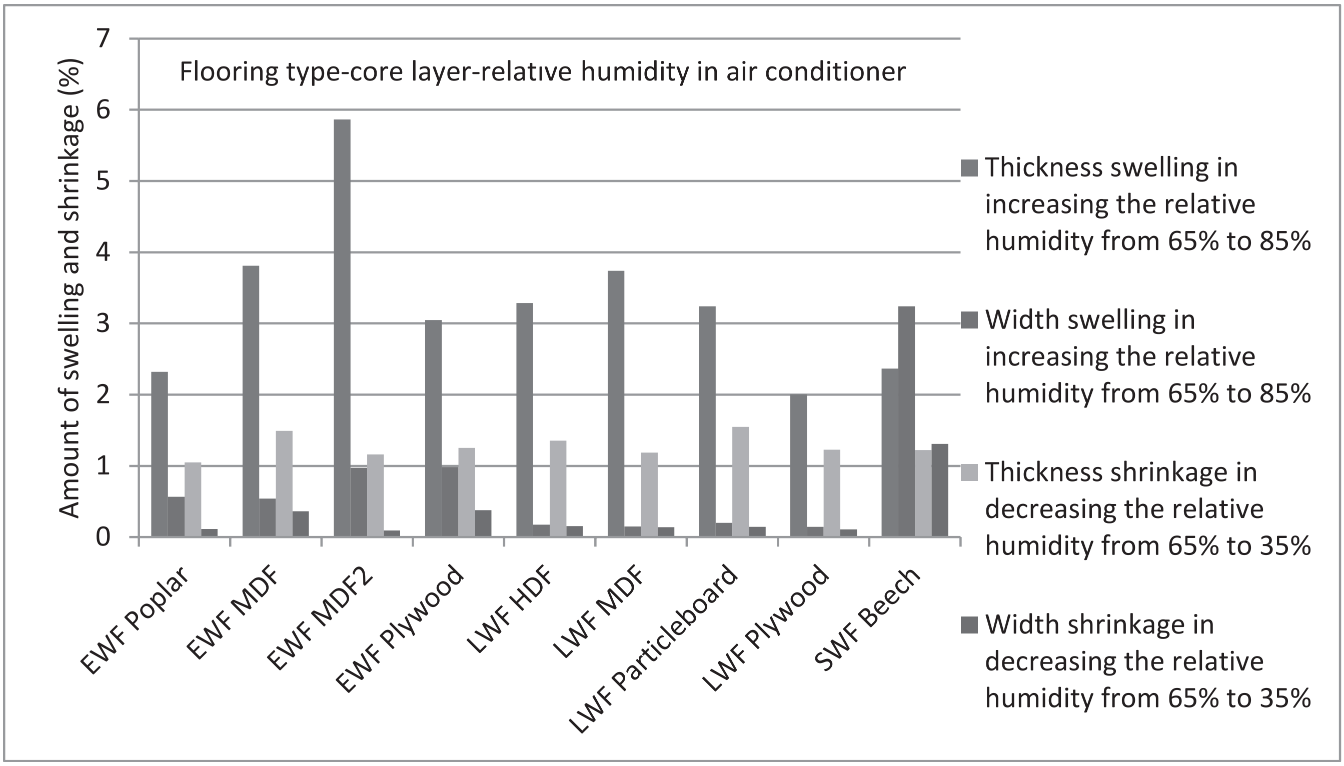

Figure 6.—Amount of thickness and width swelling, thickness, and width shrinkage depending on the relative humidity in an air-conditioning cabinet. EWF = engineered wood flooring; HDF = high-density fiberboard; LWF = laminated wood flooring; MDF = medium-density fiberboard; SWF = solid wood flooring.

Table 9.—Summary of results, discussion, and conclusion according to homogeneity groups based on statistical analysis.[a]

Environment	Test	Advisable (best)		Unadvisable (worst)	
		Flooring type	Figure	Flooring type	Figure
In water (2- and 24-h waiting time)	Increase				
	Weight	LWF (HDF); (MDF) in wet places	3	LWF (particleboard)	3
	Thickness	LWF (HDF); (MDF) in wet places	3	LWF (particleboard)	3
	Width	LWF (HDF); (MDF) in wet places	3	LWF (particleboard)	3
				SWF (beech)	1
In air-conditioning (increasing the relative humidity from 65% to 85% at 20°C)	Swelling				
	Thickness	LWF (plywood) in high-humidity places	3	EWF (MDF2)	2
	Width	LWF (HDF); (MDF) (particleboard); (plywood) in high-humidity places	3	SWF (beech)	1
In air conditioning (decreasing the relative humidity from 65% to 35% at 20°C)	Shrinkage				
	Thickness	EWF (poplar) in low-humidity places	2	EWF (MDF)	2
		LWF (plywood) in low-humidity places	3	LWF (particleboard)	3
	Width	EWF (MDF) in low-humidity places	2	LWF (plywood)	3
				SWF (beech)	1

[a] LWF = laminated wood flooring; HDF = high-density fiberboard; MDF = medium-density fiberboard; EWF = engineered wood flooring; SWF = solid wood flooring.

manufacturing management, materials selection and quality assessment.

Conclusion

The thickness, width, and weight increase rates in the case of retention of water and the shrinkage and swelling rates in the thickness and width directions in different relative humidity conditions changed depending on the type of material used in the core layer of the LWFs and EWFs.

Considering the proportions of the increase in thickness, width, and weight in water and in thickness and width in different relative humidity conditions (Tables 7 and 8, Figures 5 and 6):

1. The least dimensional mobility was seen in the LWFs because of the use of waterproof material in the lower and upper layers. This was followed by woodworking floorings and SWFs.

2. The materials used in the core layer of the LWFs and EWFs played an important role in the dimensional mobility in water. The least dimensional mobility was seen in the MDF and HDF core-layered floorings, followed by plywood, poplar, and particleboard core-layered wood floorings.
3. Apart from particleboard core-layered LWFs, SWFs are the types of floorings with the most dimensional mobility.

On the basis of these results, it may be advisable to prefer LWFs to reduce the negative effects of dimensional movements occurring under varying atmospheric conditions and water contact. In conclusion, applications reduce the water absorption properties of the materials used in production (for example, heat-treatment application, using special glues, paints, and varnishes in the structure) and may be even more effective in reducing the dimensional mobility of wood floorings.

According to the results of the data analysis, the lowest increase in water was detected in the HDF and MDF core-layered LWFs, which are advisable for wet places. In high relative humidity conditions, the lowest swelling was detected in the LWFs of all types, which are advisable for high-humidity places. In the low relative humidity conditions, the lowest shrinkage was detected in the plywood core-layered LWF, poplar, and MDF core-layered EWF types, which are advisable for low-humidity places (Table 9).

Literature Cited

American Society for Testing and Materials (ASTM). 1998. Standard practice for determination of resistance of factory applied coatings on wood products of stain and reagents. ASTM-D 3023. ASTM, West Conshohocken, Pennsylvania.

Barbuta, C., P. Blanchet, A. Cloutier, J. Deteix, and A. Fortin. 2012a. Moisture-induced stresses in engineered wood flooring with OSB substrate. *J. Wood Sci*. 58(4):327–335. DOI:https://doi.org/10.1007/s10086-012-1257-7

Barbuta, C., P. Blanchet, A. Cloutier, V. Yadama, and E. Lowell. 2012b. OSB as substrate for engineered wood flooring. *Eur. J. Wood Prod*. 70(1–3):37–43. DOI:10.1007/s00 107-010-0494-y

Belt, T., L. Rautkari, K. Laine, and C. A. S. Hill. 2013. Cupping behaviour of surface densified Scots pine wood: The effect of process parameters and correlation with density profile characteristics. *J. Mater. Sci*. 48(18):6426–6430. DOI:10.1007/s10853-013-7443-1

Blanchet, P. 2008. Long-term performance of engineered wood flooring when exposed to temperature and humidity cycling. *Forest Prod. J.* 58(9):37–44.

Blanchet, P., R. Beauregard, and B. Belleville. 2008. Prefinished oak flooring surface checking and physical properties. *Forest Prod. J.* 58(6):25–28.

Blanchet, P., R. L. Beauregard, A. Cloutier, G. Gendron, and M. Lefebvre. 2003. Evaluation of various engineered wood flooring constructions. *Forest Prod. J.* 53(5):30–37.

Bouffard, J. F. and P. Blanchet. 2009. Use of fiberboard as substrate in floating engineered wood flooring. *Forest Prod. J.* 59(11/12):6–10.

Bouffard, J. F., P. Blanchet, and C. Barbuta. 2010. Long-term performance of engineered wood flooring with oriented strand board substrate. *Forest Prod. J.* 60(6):508–513. DOI:10.13073/0015-7473-60.6.508

Glass, S. V. and S. L. Zelinka. 2010. Moisture relations and physical properties of wood. *In:* Forest Products Laboratory. Wood Handbook—Wood as an Engineering Material. General Technical Report FPL-GTR-190. USDA Forest Service, Forest Products Laboratory, Madison, Wisconsin. pp. 80–98.

Gu, H., S. Wang, T. Neimsuwan, and S. Wang. 2005. Comparison study of thickness swell performance of commercial oriented strandboard flooring products. *Forest Prod. J.* 55(12):239–245.

Guo, X., H. Wang, Q. Chen, and B. Na. 2017. The dimensional stability of engineered wood flooring in heating systems. *Wood Res*. 62(1):103–112.

Kamperidou, V., I. Barboutis, and V. Vasileiou. 2013. Hygroscopicity of thermally modified poplar (*Populus* spp.) wood. *Pro Ligno* 9(4):664–669.

Knapic, S., J. S. Machado, and H. Pereira. 2012. Properties of cork oak wood related to solid wood flooring performance. *Constr. Build. Mater*. 30:569–573. DOI:10.1016/j.conbuildmat.2011.11.014

Peng., H., J. Jiang, T. Zhan, and J. Lul. 2016. Influence of density and equilibrium moisture content on the hardness anisotropy of wood. *Forest Prod. J.* 66(7–8):443–452. DOI:10.13073/FPJ-D-15-00072

Rahimi, S., K. Singh, and D. DeVallance. 2019. Effect of different hydrothermal treatments (steam and hot compressed water) on physical properties and drying behavior of yellow-poplar (*Liriodendron tulipifera*). *Forest Prod. J.* 69(1):42–52.

Turkish Standards Institution. 1998. Plywood—Classification and terminology. Part 1: Classification. TS 3103 EN 313-1. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 1999a. Particleboards and fibreboards—Determination of swelling in thickness after immersion in water. TS EN 317. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 1999b. Wood-based panels—Determination of moisture content. TS EN 322. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 1999c. Wood-based panels—Determination of density. TS EN 323. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 1999d. Wood-based panels—Sampling, cutting and inspection. Part 1: Sampling test pieces and expression of test results. TS EN 326-1. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 2004. Wood flooring—Terminology. TS 5204 EN 13756. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 2005a. Wood, determination of moisture content for physical and mechanical tests. TS 2471. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 2005b. Wood, determination of density for physical and mechanical tests. TS 2472. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 2005c. Fibreboards—Determination of dimensional changes associated with changes in relative humidity. TS EN 318. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 2011a. Wood fibre boards—Definition, classification and symbols. TS EN 316. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 2011b. Fibreboards—Specifications. Part 5: Requirements for dry process boards (MDF). TS EN 622-5. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 2014. Wood flooring—Solid parquet elements with grooves and/or tongues. TS EN 13226. Turkish Standards Institution, Ankara.

Turkish Standards Institution. 2016. High-pressure decorative laminates (HPL)—Sheets based on thermosetting resins (usually called laminates). Part 2: Determination of properties. TS EN 438-2. Turkish Standards Institution, Ankara.

Zivkovic, V., P. Ivan, H. Turkulin, S. Tomislav, and V. J. Rajkovic. 2008. Dimensional stability of heat treated wood floorings. *Drvna Ind.* 59(2):69–73.