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Mechanical Properties of Four Timber Species Commonly Used in Turkey

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Abstract

The mechanical properties of 4 timber species (poplar, fir, pine and hornbeam) commonly used in Turkey were investigated. The compressive strength, flexural strength and toughness were determined both perpendicular and parallel to the grain. The modulus of elasticity of timber specimens was also determined parallel to the grain for the compressive test and perpendicular to the grain for the flexural test.

It was found that loading direction affects all mechanical properties remarkably. Among the timbers tested, maximum and minimum mechanical performances were obtained with the 2 hardwoods, i.e. hornbeam and poplar, respectively. The mechanical performance of the softwoods, i.e. fir and pine, was between that of the 2 hardwoods. Hornbeam showed the minimum anisotropy. Except for hornbeam, the timbers showed very low compressive strength when loaded perpendicular to the grain and very low flexural strength when loaded parallel to the grain.

Key words: Timber, Compressive strength, Flexural strength, Toughness, Modulus of elasticity.

Introduction

Timber is one of the earliest construction materials. Nowadays, it is largely superseded by concrete, steel and plastics. However, the use of timber remains quite extensive.

Basically, there are 2 types of lumber for carpentry: softwoods and hardwoods. These are somewhat misleading terms, because they refer not to the quality of timber, but to the types of tree the timber comes from. Softwoods generally come from trees with needle-like leaves (conifers); they are “evergreens”. They are not normally highly durable unless protected by preservatives. Hardwoods comprise the broad-leaved trees, mostly deciduous, although there are many broad-leaved trees that are evergreen in certain climates. Many hardwoods are in general durable, and some such as oak may last for centuries without the use of preservatives (although, exceptionally, balsa and poplar are also hardwoods and these are neither strong nor durable). Generally, the hardwoods are harder and stronger than the softwoods. Hardwood trees are slow growing, which makes them more expensive than softwoods. Hardwoods generally are used more extensively for furniture, interior finishing, and cabinetwork than for structural purposes (Erdoğan, 2002; Taylor, 2002; Keyser, 1986).

Poplar is a lightweight, fine-grained wood suitable for furniture, cabinets and trim. Typically white to yellow-brown, poplar is one of the least expensive hardwoods. Owing to its extreme softness, it can be easily cut. Poplar takes paint well. The wood of hornbeams is very hard and difficult to work, restraining its use. Its hardness has, however, lent it to use for carving boards, tool handles, coach wheels and other situations where a very tough, hard wood is required. It is sometimes coppiced to provide hardwood poles. Pine is a weak, soft and light timber with a tendency to shrink. Fir is the strongest of the softwoods. Although heavy, it is resistant to warping and shrinking and suitable for framing and subflooring (Black, 2004).

Timber is a very variable material and for many of its parameters, such as density, cell length and microfibrillar angle of the S_2 layer (the middle layer of the secondary wall), distinct patterns of variation could be established within a growth ring, outwards from the pith towards the bark, upwards in the tree, and from tree to tree. The effects of this variation in structure are all too apparent when mechanical tests are performed (Dinwoodie, 2000).

Anisotropy in strength is due in part to the cellular nature of timber and in part to the structure and orientation of the microfibrils in the wall layers. Bonding along the direction of the microfibrils is covalent while bonding between microfibrils is by hydrogen bonds. Consequently, since the majority of microfibrils are aligned at only a small angle to the longitudinal axis, it will be easier to rupture the cell wall if the load is applied perpendicular than if applied parallel to the axis. Furthermore, cellulose $(C_6H_{10}O_5)_n$ occurs in the form of long, slender filaments or chains, these having been built up within the cell wall from the glucose monomer $(C_6H_{10}O_5)$. Whilst the number of units per cellulose molecule can vary considerably even within one cell wall, it is thought that a value of 8000-10,000 is a realistic average for the secondary cell wall, while the primary cell wall has a degree of polymerization of only 2000-4000. Hemicelluloses, like cellulose itself, are carbohydrates build up of sugar units. Both the degree of crystallization and the degree of polymerization of the hemicelluloses are generally low, the molecule containing less than 200 units; in this respect the hemicelluloses are quite different from true cellulose. Lignin is chemically dissimilar to hemicelluloses and to cellulose; it has a non-crystalline structure. Lignin is a complex, 3-dimensional, aromatic molecule composed of phenyl groups with a molecular weight of about 11,000 (Dinwoodie, 2001).

The tensile strength of clear, straight-grained timber is much higher than its compressive strength when measured parallel to the grain, since compression causes buckling or plastic crushing of the fibers. However, in structural timber containing knots and distorted grain, the opposite is the norm. Failure in tension is mainly due to shear failure between fibers or cells. Bending stresses are very commonly applied to timber in service and, as would be expected, flexural strength, as measured by the modulus of rupture, is between tensile and compressive strength (Dinwoodie, 2001; Taylor, 2002).

The elastic moduli and crushing strength of timber are related to the bending, buckling, plastic collapse and fracture of the members making up the cell walls (Easterling et al., 1982).

One of the most important factors that affect the mechanical properties of timber is its moisture content. The strength of clear timber rises approximately linearly as moisture content decreases from the fiber saturation point and may increase 3-fold when the oven-dry state is reached. However, toughness decreases with drying. At moisture contents of around 15%, the strength would be approximately 40% higher than that of the saturated state, depending on the type of wood. The mechanism of the strength increase is similar to that of shrinkage in concrete; the contraction results in decreased inter-fiber spacing and, therefore, stronger bonding between fibers (Baradan, 2002; Taylor, 2002; Widehammar, 2004).

The presence of defects such as checks, cross grain, knots, pitch pockets, shakes, and warp causes a considerable reduction in the mechanical properties of the timber. Thus the presence of defects should be considered in the design of structural members. For example, beams should be positioned with the knots in the compression region if possible, since knots exert a weakening effect in tension (Keyser, 1986).

In the present study, the compressive strength, flexural strength, toughness and modulus of elasticity of 4 types of timber were studied both parallel and perpendicular to the grain.

Experimental Work

All timber samples used in this study were taken from the sapwood region of individual trees. Firstly, the moisture content of timber specimens was determined. For this purpose, the specimens were kept in an electrical oven at 105 °C for 24 h as per ASTM D143. The moisture content and density of the timber specimens are given in Table 1. The moisture contents of the timber species were quite close to each other and about 15%. Thus, the specimens were not exposed to drying before the mechanical tests were applied.

Table 1. The moisture content and density of timber specimens.

	Poplar	**Fir**	**Pine**	**Hornbeam**
Moisture, %	16.1	14.7	13.5	15.5
Density (dry), g/cm^3	0.334	0.328	0.365	0.532

The mechanical properties of timber were determined on small, knot-free, straight-grained, perfect test specimens, which represent the maximum quality of wood. As such, these test pieces are not representative of structural-size timber with all its imperfections. This is why several arbitrarily defined reductions have to be used in order to obtain a measure of the working stresses of the timber when small, clear test pieces are used. However, the small clear test piece is valid for characterizing new timbers and for the strict academic comparison of wood from different trees or different species (Dinwoodie, 2001).

The compressive strength of timber specimens was determined on 50 mm cubic specimens both parallel and perpendicular to the grain. Grain directions of timber are shown on a tree in Figure 1. The cross-sectional area of the test samples is in conformity with ASTM D143-52. These tests were performed by using a load controlled hydraulic testing machine at a loading rate of 0.2 MPa/s. Furthermore, to obtain stress-strain curves, a dial gage with precision of 0.001 mm was used to determine specimen deformation under load. The deformation was measured from the change in distance between the loading plates (Figure 2). The slope of the linear part of the stress-strain curves was used to determine the modulus of elasticity of the samples.

Prismatic specimens 20 mm x 20 mm in cross section and 300 mm long, resting on a span of 200 mm, were used to determine the flexural strength and toughness with a 3-point bending test using a stroke controlled testing machine. In this test, the beams were deflected at a constant crosshead speed of 1 mm/min. The mid-span deflection values were determined on the crosshead of the testing machine. The applied loads and corresponding mid-span deflections were recorded simultaneously by a computer at a rate of 5 Hz. The toughness was regarded as the area under the load-displacement curves. The load vs. mid-span deflection relationship was determined up to a deflection value of 20 mm. The maximum flexural strength of samples was calculated using Eq. (1).

$$f_{flex}(MPa) = \frac{3.P.L}{2.b.h^2} \tag{1}$$

where P is the maximum load in Newtons, L is the span length in millimeters, b is the width of the beam in millimeters, and h is the height of the beam in millimeters.

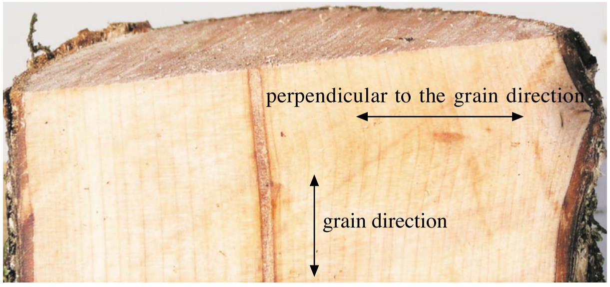


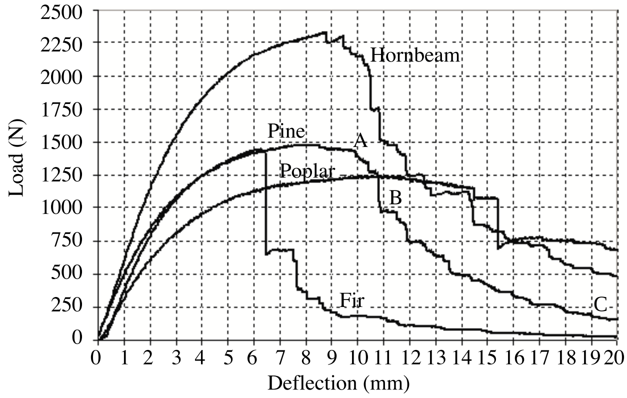
Figure 1. Grain directions on a tree.

Figure 2. Compression test set-up.

The modulus of elasticity was determined from the bending test data using Eq. (2).

$$E(MPa) = \frac{P.L^3}{48.I.y} \tag{2}$$

where P is the bending load, y is the corresponding mid-span deflection at this load, and I is the moment of inertia. P/y values were determined from the slope of the initial linear portion of the load-deflection curves (Figure 3).



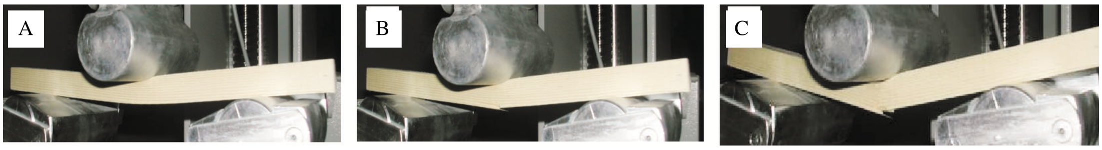


Figure 3. Load-deflection curves of timber under flexural load perpendicular to the grain.

Results and Discussion

The results obtained from the compressive and 3-point bending tests are given below.

Compression test

Although in many applications the timber is subjected to compression parallel to the grain, in some cases such as joists bearing on a beam the member is loaded perpendicular to the grain. This is why both the compressive strength parallel to the grain and the compressive strength perpendicular to the grain are of importance. The compression test was carried out both parallel and perpendicular to the grain. The results are the average of 3 specimens. Stress-strain curves of timber specimens loaded parallel to the grain are given in Figure 4, in which only a limited portion of the stress-strain curve is seen. Under compressive loading after the linear region the stress becomes constant or a drop can be seen. This part of the curve is defined as yielding and the stress in the plateau region is called yield stress or yield strength. After the plateau region (beyond a strain level of 0.016) the densification of material takes place under compression and the stress rises again. However, Figure 4 defines the proportional limit and the maximum stress level of the material before yielding.

The point of inflection on the ascending part of the load-deflection curve, known as the proportional limit, was determined as 42, 24, 18 and 10 MPa for hornbeam, fir, pine and poplar, respectively, as shown in Figure 4.

In Table 2, the average compressive strength and modulus of elasticity of timber specimens are given with standard deviation values in brackets.

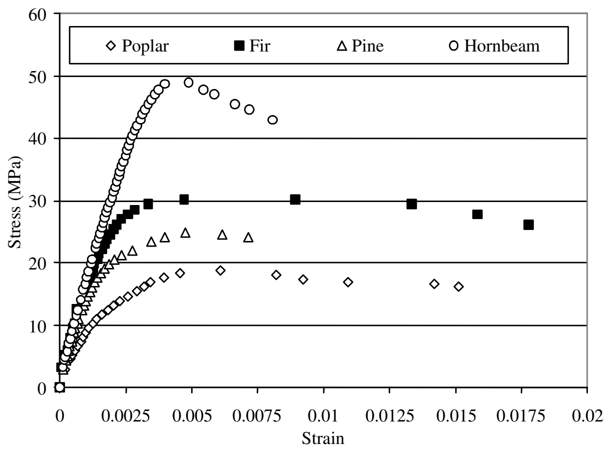


Figure 4. Compressive stress-strain curves of timber loaded parallel to the grain.

Table 2. Compressive strength and modulus of elasticity (parallel and perpendicular to the grain).

	Compressive strength (MPa)			Modulus of elasticity (MPa)
Orientation	$\|\|^*$	$\perp^{**}$	$\|\| : \perp$ ratio	$\|\|$
Poplar	18.2 [0.4]***	1.9 [0]	9.6	5860 [1142]
Fir	32.3 [0.2]	2.6 [0.2]	12.4	13,810 [665]
Pine	26.9 [2.4]	2.2 [0.3]	12.2	12,750 [884]
Hornbeam	48.3 [2.8]	10.0 [0.6]	4.8	15,260 [770]

*||: parallel to the grain.

**⊥: perpendicular to the grain.

*** Numbers in brackets denote the standard deviation values in MPa.

As expected, compressive strength parallel to the grain is much greater than that perpendicular to the grain. About 90% of the cells are aligned vertically (known as grain) and the remaining percentage is present in bands (known as rays). This means that there is a different distribution of cells on the 3 principle axes; this is the main reason for the anisotropy present in timber. This is due to the fact that the resistance of wood perpendicular to the grain is simply a matter of the resistance offered by the wood elements to being crushed or flattened. Therefore, the strength of wood under forces perpendicular to the grain is relatively small (Erdoğan, 2002). Depending on the type of timber, the ratio of compressive strength parallel to the grain to that perpendicular to the grain varies between 4.8 and 12.4. As can be seen from Table 2, hornbeam gave the lowest parallel to perpendicular strength ratio, as an indication of the low degree of anisotropy among the tested timber under compression.

Maximum compressive strength was obtained for hornbeam both parallel and perpendicular to the grain (Table 2). This was followed by fir, pine and poplar, in descending order. In the case of applying the load parallel to the grain, failure involves either buckling or bending of the individual fibers.

Among the tested species, hornbeam showed the maximum modulus of elasticity, 15.3 GPa. The moduli of elasticity of pine and fir were close to each other while poplar had a relatively low modulus of elasticity of 5.9 GPa. Hearmon (1948) reported that the moduli of elasticity (parallel to the grain) of 4 different softwoods and 6 different hardwoods are 6-16 GPa (Dinwoodie, 2001). Due to the relatively high capacity of the load cell used in this study, the modulus of elasticity of timber species could not be determined perpendicular to the grain. However, it is well known that the modulus of elasticity parallel to the grain is always larger than that perpendicular, partly because the microfibrils of cellulose in the cell wall lie closest along that direction, making the cell wall stiffest against axial deformation (Easterling et al., 1982).

Flexural test

The 3-point flexural test was carried out both parallel and perpendicular to the grain. Averages of at least 3 specimens were reported. Flexural strength, toughness, mid-span deflection at maximum load and modulus of elasticity of timber both parallel and perpendicular to the grain are given in Table 3. In Figure 3 selected load-deflection curves of timber perpendicular to the grain are presented with pictures of various stages of deformation of pine under different load levels. In this test, the upper compression layer of the specimens buckled, causing the neutral axis to move downwards during the test so that, ultimately, the lower part of the specimen failed in tension. A similar conclusion was reached by Taylor (2002). Dinwoodie (2001) shares the same idea for knotty timber. As shown in Figure 3, there is an instantaneous drop in load after the maximum point; then the load decreases gradually.

Table 3. Flexural strength, toughness, mid-span deflection at maximum load and modulus of elasticity of timber (parallel and perpendicular to the grain).

	Flexural strength (MPa)		Toughness (N.mm)		Mid-span deflection at maximum load (mm)		Modulus of elasticity (MPa)
	∥	⊥	∥	⊥	∥	⊥	⊥
Poplar	2.2 [1.36]*	40.2 [6.76]	501 [112]	14,825 [1450]	8.0 [3.19]	10.7 [0.5]	3783 [656]
Fir	2.7 [1.07]	53.3 [5.76]	373 [116]	9566 [1358]	7.4 [1.54]	5.8 [0.6]	5713 [544]
Pine	2.8 [1.16]	56.8 [2.83]	540 [140]	16,574 [793]	8.5 [1.23]	9.6 [1.6]	5554 [288]
Hornbeam	9.4 [1.22]	87.4 [7.32]	3084 [1272]	30,323 [3421]	10.9 [1.01]	9.7 [2.0]	7500 [574]

*Numbers in brackets denote the standard deviation values.

The maximum flexural strength was obtained for hornbeam under loading perpendicular to the grain. This was followed by pine, fir and poplar, in descending order. As shown in Table 3, mid-span deflection at maximum load values for loading perpendicular to the grain is similar in poplar, pine and hornbeam. However, mid-span deflection at maximum load for fir is approximately half that of the others. Therefore, minimum toughness of 9566 N.mm is obtained from fir, as a result of low load carrying capacity after maximum load up to 20 mm deflection. Hornbeam has the maximum toughness value among the tested species. The toughness of hornbeam is about 2 times greater than that of pine and poplar, and 3 times greater than that of fir. Under flexural load, hornbeam showed the maximum modulus of elasticity, followed by fir, pine and poplar. However, the moduli of elasticity of fir and pine were very close to each other.

Maximum flexural strength of 9.4 MPa was obtained for hornbeam for loading parallel to the grain. Nevertheless, 2.2, 2.7 and 2.8 MPa flexural strength values were obtained for poplar, fir and pine, respectively. Maximum deflection at maximum load values are close to each other, varying between 7.4 and 10.9 mm. The toughness of hornbeam, which has maximum flexural strength and mid-span deflection at maximum load, is considerably greater than that of the other timbers.

The ratios of flexural strength and toughness values perpendicular to the grain and parallel to the grain are presented in Figure 5. Larger ratios of both flexural strength and toughness values are measures of the degree of anisotropy of the timber. In this respect, hornbeam, which has relatively high density among the tested timbers, seems to be less anisotropic than the other 3 species. By the increment of density, a reduction in anisotropy has been reported by Easterling et al. (1982).

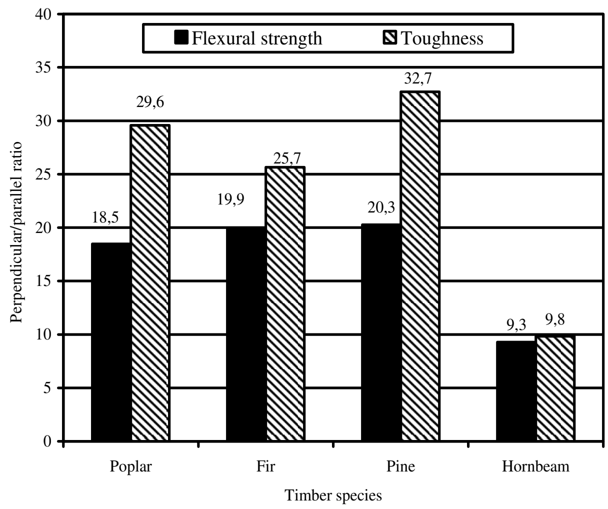


Figure 5. Perpendicular/parallel ratio of some mechanical properties of timber.

Relationship between density and mechanical properties

The density of timber is a function of both cell wall thickness and cell cavity. There is a good correlation between strength and density of timber; thus density is the best predictor of timber strength (Dinwoodie, 2001). The relationship between specific gravity and mechanical properties within a species has been studied by many researchers. A significant linear relationship between specific gravity and mechanical properties of timber was reported by Shepard and Shottafer (1992) and Zhang (1995). Zhang (1997) showed that modulus of rupture and the maximum crushing strength in compression parallel to the grain are most closely and almost linearly related to specific gravity, whereas modulus of elasticity is poorly and least linearly related to specific gravity.

The relationships between density and compressive strength parallel to the grain and flexural strength perpendicular to the grain and toughness perpendicular to the grain are given in Figures 6 and 7, respectively. As shown in these figures, an increment in density results in higher mechanical properties.

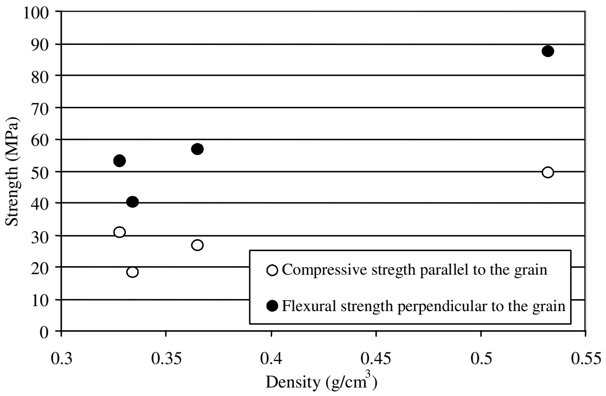


Figure 6. Relationship between compressive strength parallel to the grain and density.

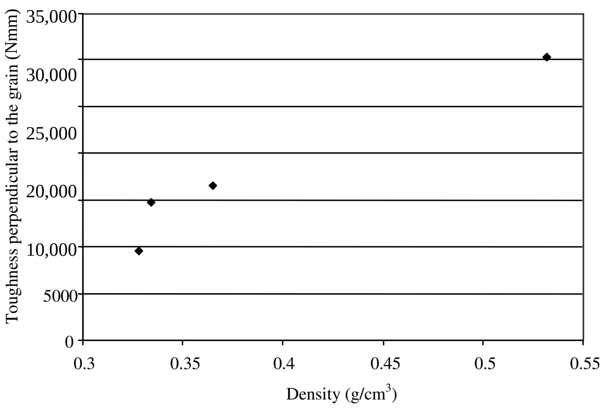


Figure 7. Relationship between toughness perpendicular to the grain and density.

Relationship between various mechanical properties

In practice, bending stresses are generally applied perpendicular to the grain of timber while compressive stresses are applied mostly parallel to the grain in order to benefit from the high mechanical properties of timber. Therefore, the relationships between these mechanical properties were determined in the present study.

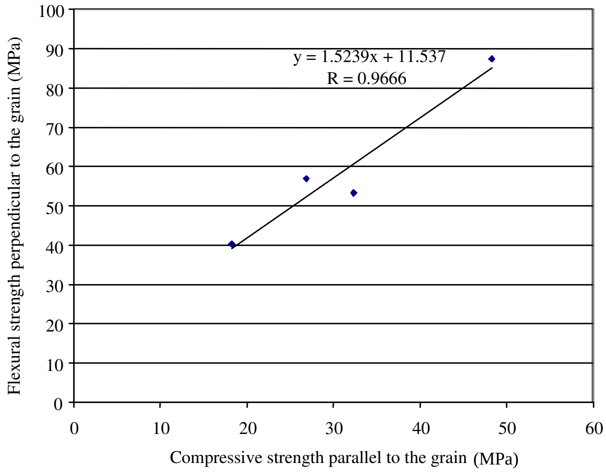


Figure 8. Relationship between compressive strength parallel to the grain and flexural strength perpendicular to the grain.

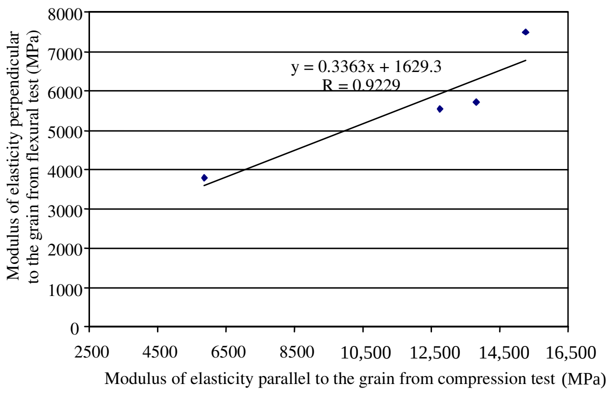


Figure 9. Relationship between modulus of elasticity parallel to the grain under compression load and perpendicular to the grain under flexural load.

Relationships between compressive strength parallel to the grain and flexural strength perpendicular to the grain are given in Figure 8. There is a linear correlation between these 2 mechanical properties. The coefficient of linear regression is 0.9666. In addition, there is a good correlation, with the coefficient of regression of 0.9229, between the modulus of elasticity parallel to the grain under compression load and perpendicular to the grain under flexural load as shown in Figure 9.

Conclusions

The following conclusions may be drawn from the present study:

- Loading direction affects all mechanical properties remarkably due to the anisotropic nature of timber. Among the timber species tested, the minimum anisotropy in mechanical properties was observed in hornbeam.
- The compressive strength of timber when loaded parallel to the grain is greater than that of timber loaded perpendicular to the grain. The ratio between these strength values varied from 9.6 to 12.4 for poplar, fir and pine. The corresponding value is only 4.8 for hornbeam due to its lower anisotropy.
- Irrespective of the direction of loading, hornbeam showed the highest compressive strength, flexural strength and modulus of elasticity, while poplar had the lowest values. For fir and pine, these mechanical properties were significantly close to each other.
- Flexural strength and toughness values of timber specimens when loaded perpendicular to the grain were greater than the corresponding values when loaded parallel. The maximum flexural strength perpendicular to the grain was obtained from hornbeam. This was followed by pine, fir and poplar. Although the flexural strength of fir was greater than that of poplar, the toughness of poplar was greater than that of fir due to the low load carrying capacity of fir after the maximum load. The mid-span deflection of fir at the maximum load level was about half that of the others. This is an indicator of the relatively brittle behavior of fir under flexural load.
- The maximum toughness parallel to the grain was obtained for hornbeam. This was followed by pine, poplar and fir, in descending order.
- Under flexural load perpendicular to the grain, the maximum modulus of elasticity of timber specimens was obtained for hornbeam. This was followed by pine, fir and poplar, in descending order.
- There is a strong relation between compressive strength and density. Among the tested timbers, hornbeam, with higher density, showed the maximum mechanical properties such as compressive strength parallel to the grain, flexural strength and toughness perpendicular to the grain. Moreover, a high correlation was found between compressive strength parallel to the grain and flexural strength perpendicular to the grain.

References

ASTM D143, Standard Methods of Testing Small Clear Specimens of Timber.

Baradan, B., “Materials for Civil Engineering”, DEU Engineering Faculty Press, İzmir 2003 (in Turkish).

Black, A.D., “Picking the Right Lumber is an Important Decision”, www.cumberlink.com/fall_home/lumber.php, 2004.

Dinwoodie, J.M., “Construction Materials-Their Nature and Behavior”, Edited by Illston J.M, and Domone P.L.J. Spon Press, Taylor & Francis Group, London and New York, 2001.

Dinwoodie, J.M., “Timber - Its Nature and Behavior”, E & FN Spon, Taylor & Francis Group, London and New York, 2000.

Easterling, K.E., Harrysson R., Gibson L.J. and Ashby M.F., “On the Mechanics of Balsa and Other Woods”, Proc. R. Soc. Lond., A 383, 31-41, 1982.

Erdoğan, T.Y., “Materials of Construction”, METU Press, Ankara, 2002.

Keyser, C.A., “Materials Science in Engineering”, Charles E. Merrill Publishing Company, Columbus, USA, 1986.

Shepard, R.K., Shottafer, J.E., “Specific Gravity and Mechanical Property - Age Relationships in Red Pine”, Forest Prod. J., 42, 60-66, 1992.

Taylor, G.D., “Materials in Construction Principles, Practice and Performance”, Pearson Education Limited, Malaysia, 2002.

Widehammar S., “Stress-Strain Relationships for Spruce Wood: Influence of Strain Rate, Moisture Content and Loading Direction”, Society for Experimental Mechanics, 44, 44-48, 2004.

Zhang, S.Y., “Effect of Growth Rate on Wood Specific Gravity and Selected Mechanical Properties in Individual Species from Distinct Wood Categories”, Wood Science and Technology, 29, 451-465, 1995.

Zhang, S.Y., “Wood Specific Gravity-Mechanical Property Relationship at Species Level”, Wood Science and Technology, 31, 181-191, 1997.