Prediction of bending strength in oak beams on the basis of elasticity, density and wood defects

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Abstract: The purpose of the study was to propose accurate models for predicting bending strength that are valid for a wide range of beam qualities. For the study, 26 European oaks (*Quercus robur* L.) were felled in northwestern Spain, where most of the oak stands in the country are located. The trees were sawn, and a sample of quarter-sawn planks was selected. Planed and edged specimens (5×10×200 cm) were tested to obtain the modulus of rupture (MOR) in axial direction bending, the modulus of elasticity (MOE), density, moisture content, and size of defects. The MOR was correlated with the MOE and with maximum edge knot diameter. The correlation was not high enough to justify construction of a predictive model of mechanical behavior on the basis of maximum knot size in the piece. The analyses enabled development of a model for predicting MOR, with MOE as the only predictor variable (R^2=0.65; bias=0.6%).

Subject headings: Mechanical properties; Wood structures; Bending; Stiffness; Wood beams.

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Introduction

Oak wood has traditionally been used in Spain for structural purposes because of its durability and mechanical strength. It was originally used to produce ceiling joists, purlins and roof truss members within fabric or stone structures (Nassar 1996), but in the 20th century use of oak beams in structures declined as a result of the increased use of concrete, steel and graded softwood. This has led to a reduction in the pressure on oak forests, which are currently expanding in Spain (Xunta de Galicia 2001). Approximately 95% of the oak timber (*Quercus robur* and some *Q. petraea*) produced in Spain in 2007 (181225 m^3 over bark) originated from Galicia (NW Spain), where oak is the top deciduous tree in terms of volume harvested (Ministerio de Medio Ambiente, y Medio Rural y Marino 2009).

Sawn hardwood production in Spain has been greatly affected by a reduction in demand since 2008, within an overall environment of deep economic and financial problems. There has also been a very large reduction in sawn hardwood production in Slovakia and Romania (one third of the sawn hardwood produced in Europe in 2008 was produced in Spain, Slovakia and Romania). However, the consumption of sawn oak is relatively stable in Europe because the increased interest shown by architects and designers in the use of oak wood for building and flooring, has compensated the reduction in sawn oak consumption by the furniture industry (UNECE/FAO 2009).

The most common uses for oak timber in construction are for prefabricated buildings, agricultural buildings and storehouses (Riesco 2001). It is sometimes also used in new buildings where a traditional appearance is desired (e.g., Shanks and Walker 2009) and also in the restoration of old buildings to replace pieces and to calculate timber strength in building work (e.g., Yeomans 1999).

Use of the species is restricted by the high variability in density and other quality-related characteristics (Riesco 2001; Zhang et al. 1994). In addition, visual grading of Spanish oak timber destined for structural purposes is not still standardized and, therefore this type of wood is at present not assignable to the EN 338:2003 European strength classes (European Committee for Standardization 2003).

Selection of oak wood as a construction material should be based on detailed knowledge of its physical and mechanical properties. These should be tested on specimens of structural size and with defects, so that realistic conditions are reproduced in order to consider the influence of defects on strength properties. Executing tests with technological dimension specimens is expensive and complicated because of the large dimensions of pieces for use (Mitre 1988). However, the alternative method of testing small defect-free specimens and implementing reduction factors to obtain mechanical properties has been reported to be of little use with oak wood (Green and McDonald 1993; McLeod III and McLain 1987).

Bending strength and modulus of elasticity are the main timber properties used to determine the end use of wood for structural purposes. Bending is the most frequent effort in wood used in construction (beams, spars and carpentry elements). Estimation of the modulus of rupture (MOR), measured as bending strength parallel to grain (i.e., bending strength when the load is perpendicular to the direction of grain and is perpendicular to the axial direction of the tested member) is therefore essential for the mechanical characterization of wood, and the modulus of elasticity in bending (MOE) is required to quantify the behavior of a piece being deformed under mechanical stress. If the wood is readily deformed, sizing in structural calculations should consider excessive deflection or buckling risk and not consider the probability of static failure under bending forces.

The goals of the present study were to identify physical variables that are useful for predicting bending behavior in structural sawn oak timber, and to propose accurate models for predicting MOR that are valid for a wide range of beam qualities.

Materials and methods

Twenty-six oak trees (*Quercus robur* L.) were felled in Galicia for use in the present study, and care was taken to include a number of trees that amply covered the requirements of European standard EN 384:2004 for hardwoods (European Committee for Standardization 2004a): at least 40 specimens by sample taken from at least five trees. The aim of the tree sampling was to cover the high interindividual variability in oak timber properties (Riesco 2001; Zhang et al. 1994). Only specimens suitable for sawing were sampled, i.e., those with straight stems, breast height diameter ranging from 30 to 60 cm, more than 3 m of merchantable wood in the stem and absence of any apparent rot. The age of the sampled trees was between 33 and 96 years.

Each stem was cut into 210 cm long logs. All logs were then sawn following a simplified radial sawing pattern in order to produce quarter-sawn planks of thickness 7 cm, width 12 cm (Fig. 1) and length slightly more than 2 m. The 75 planks with the most clearly radial orientation were selected, as the sapwood tends to be located at the edge in such pieces, which are dimensionally more stable while drying, although the water readily passes through in radial direction. Selection was made from the sawing pattern diagrams to avoid the external appearance of the planks influencing the choice.

Fig. 1

The selected planks were air-dried for an average of 742 days (range 302 - 910 days). This slow drying process was used to prevent development of the checks and distortions that often occur in rapidly dried oak timber. This drying time was considered sufficient because, according to Collardet and Besset (1992), the air-drying time for 5 cm-thick oak pieces is 455 days.

The dried planks were butted-off and planed to the target dimensions (5×10×200 cm) for carrying out the structural tests of specimens in accordance with European standard EN 408:2004 (European Committee for Standardization 2004b). The bending properties (MOR and MOE), apparent density, moisture content, dimensions, external features and apparent defects in each beam were measured and recorded (Table 1). The grain slope was computed as the tangent of the angle between the grain direction and the lateral arris. The slope of grain was determined on the face of the beam by taking a line parallel to surface checks. The general grain slope was determined over as large a distance as possible in the specimen and the local grain slope was measured in the area of the beam where the slope was greatest.

The local modulus of elasticity in bending and the simple bending strength were obtained in each beam by an edgewise four-point static bend test, in accordance with standard EN 408:2004 (European Committee for Standardization 2004b). Each specimen was tested with the growth rings perpendicular to direction of loading, i.e., the load was applied on the tangential face (Fig. 2). A universal testing machine (IBERTEST, model ELIB-100-CO) with a mobile cross loading-head that can generate a force of 100 kN was used for the mechanical tests, which were carried out under laboratory environmental conditions (temperature=16ºC; relative humidity=60%). The velocity of vertical advance of the loading-head was a standardized value of 0.30 mm s^{-1} for all pieces. To maintain the isostatic forces in the system (simply supported beam), steel plates were placed between the supports and the surface of the wood to prevent local flattening of the beams on the supports.

As a result of the tendency for the members to twist when loaded, lateral stops were used to brace the compression zone to prevent the beam buckling or overturning, although lateral movement does not occur when the dimensions of the cross-section are such that the depth-to-thickness ratio is relatively small. In this experimental layout, lateral instability was unlikely as the ratio was 2, less than 4 recommended by Desch and Dinwoodie (1996). The slenderness ratio was also calculated as this is a more accurate method of accounting for lateral instability. The slenderness ratio includes the length of the beam as well as the dimensions of the cross-section. In this case the slenderness ratio was much lower than the maximum recommended value of 50 (Breyer et al. 2007).

Fig. 2

In order to calculate the MOE, the vertical deformation of the elastic curve was measured with a steel lath, carried on the ends of the central segment of each beam. The lath was fitted with a gauge that measures differences in vertical deformation between ends of the segment and the central point (Fig. 2). In bending strength testing (to failure) the deformation gauge was removed and the sensor-codifier fitted in the transmission system of the machine was used. The curve obtained for forces (in kN) versus deformations (in mm) was recorded for each static bending test, for 500-1000 pairs of values. The specimens were classified into two groups, depending on the type of failure: (i) beams that failed in the neighborhood of a defect, and (ii) beams that failed in the lowest fibres, subjected to tension parallel to the grain.

The influence of the shear force was considered negligible on beam deformation because this is measured in the span between load points, an area of the beam in which shear efforts are null. Additionally, shear stress is assumed to be negligible in this case because members were very slender (span between supports at least 14 times the thickness).

The wood at the centre of the span is more moist, and therefore weaker, than at the ends of the piece. Failure was therefore expected to be located near the centre of the span.

Following the bending test, wood moisture, apparent density, ring width and percentage of sapwood were determined on a 2 cm-width slab removed from the complete transverse section of each beam tested, in a knot-free area. The moisture content was computed according to standard EN 13183-1:2002 (European Committee for Standardization 2002), on the basis of the difference in weight between the air-dry state and the oven-dry state, and was expressed as percentage of the weight in the oven-dry state. The apparent density was obtained according to standard ISO 3131:1975 (International Organization for Standardization 1975), on the basis of the quotient between weight and volume of the slab in the air-dry state. Sapwood was detected by use of methyl orange dye.

The experimental values of modulus of elasticity (MOE_H) and bending strength (MOR_H) were not always obtained at the standard wood moisture content. These were therefore converted to values (MOE and MOR) at a standard moisture content of 20%. The correction was made by means of equations (1) and (2), proposed by Riesco (2001) for the same species and provenance, in bending tests on defect-free specimens in a range of wood moisture content covering the range considered in this study:

$$MOR = MOR_H[1 + 0.044(H - 20)] \quad (1)$$

$$MOE = MOE_H[1 + 0.043(H - 20)] \quad (2)$$

where MOR is the bending strength, modulus of rupture, in N mm^{-2} at a standard moisture content of 20%

MOR_H is the bending strength, modulus of rupture, in N mm^{-2} at moisture content H

MOE is the modulus of elasticity parallel to grain in N mm^{-2} at a standard moisture content of 20%

MOE_H is the modulus of elasticity parallel to grain in N mm^{-2} at the moisture content H

H is the moisture content of the tested beam.

The equations were fitted by ordinary least square regression. All the statistical analyses were executed by means of PASW Statistics 18 software (IBM 2010).

Results and discussion

A total of 66 mechanical tests were found to be valid after 12% of the tests were rejected because of deficiencies in the operational process, such as failure at the start of the bending test, recording errors and test times outside the range established in the standard test method EN 408:2004 (European Committee for Standardization 2004b).

Despite the high strength of some tested beams, no instability due to buckling was observed. As mentioned in Materials and methods, the buckling phenomenon was not expected owing to the shape of the specimens.

Despite the large range in drying time, the coefficient of variation for moisture content of the beams was only 12.7% (Table 1). This can be explained if it is considered that the drying process was within a relatively narrow range (750 - 850 days) in most of the beams tested (73%). The drying process was very slow because of the thickness of the planks, the high density of oak wood and the radial orientation of the pieces (which hampered movement of the water). Thus the moisture content of approximately only one third of the pieces, measured on a slab removed from each beam tested, decreased to 20% or lower (20% is the reference value considered in standard EN 408:2004 for mechanical tests: European Committee for Standardization 2004b). This rule establishes that for dense hardwoods, in which it is difficult to reach the reference moisture content, the test could be carried out at another level of moisture, which should be recorded. However, the moisture content in the bending strength test must not exceed 25% because at higher values, failure may occur as a result of axial compression (Farmer 1972). In the present study, only one of the four test beams in which the moisture content exceeded the threshold value broke as a result of axial compression.

The test results revealed higher dispersion than expected in mechanical properties, despite the homogeneity of the sample as regards moisture and density. The variation in mechanical behavior (as measured by the coefficients of variation of MOR and MOE) is therefore mainly explained by the large variation in the presence of apparent defects (Table 1).

In a beam with defects, failure begins with the opening of a fissure due to tensile stress perpendicular to the grain in the neighborhood of a knot or some other discontinuity that forces the grain to deviate and leads to locally steep grain slope. The length of the fissure increases with load, leading to the rupture of the cell wall and the piece finally splits owing to tension perpendicular to the grain (Desch and Dinwoodie 1996). In high quality specimens, with few defects, failure begins with compression stress parallel to the grain. It is assumed that at the initial stages of loading (elastic state in tension and compression), deformed sections are plain and that the stress follows a bitriangular distribution with the common apex in the neutral line. The distribution profile is formed by two straight lines with different slopes because the modulus of elasticity is not the same in tension and in compression parallel to the grain. At this stage, the neutral fiber decreases very slightly from its position without any load. As the load increases, compression failures develop at the upper surface (cell crushing). The upper fibers deform when the stress exceeds the limit of elasticity parallel to the grain and the stress distribution then takes on a parabolic shape. The neutral axis moves towards the lower surface, leading to a greater increase in edge tensions, and finally the piece fails quickly due to breakage of fibers subject to tension parallel to the grain, even though the wood presents its best strength properties under tension parallel to grain. The failure occurs quickly because the elastic limit is very close to the failure limit in this type of stress.

Among the variables studied, only MOE, MOR, and the proportion of sapwood in the cross-section of the beam differed significantly between the two types of failure (i and ii) described in Materials and methods. The results of the one-factor analysis of variance are shown in Table 2. The sapwood was on average 11.2% of the cross-section in group (i) beams, and on average 27.3% in group (ii) beams, and therefore specimens with little sapwood usually fail close to a defect. This suggests that the abundance of sapwood, which is peripheral wood in the stem, was related to a low presence of defects, mainly located in the inner region of the stem (knots, pith, juvenile wood, or tension wood).

It is well known that increasing the beam dimensions (length and cross-section) has an adverse effect on the strength of the beam, as defects are more likely to occur in larger members (Castéra and Toratti 1999; Chui 1991). In the present study, type (i) failures would be more likely in thicker and deeper beams because the proportion of sapwood would be lower and the number of defects would be higher because of the proximity to the center of the stem in quarter-sawn blanks.

As regards apparent defects, the presence of pith, checks, and heterogeneous ring widths did not have significant effects on either MOR or MOE in the sample. The Pearson's coefficients of correlation for the variables listed in Table 1 were only significant in the cases of MOR, MOE, and maximum edge knot diameter. It is noticeable that percentage of sapwood was not significantly correlated with MOR or MOE (p>0.05), despite the highly significant influence of sapwood in the type of failure mentioned above. The significant correlations in the matrix of correlations are indicated in Table 3.

Moisture content and MOR_H were not significantly related because the defects in structural timber determine the bending performance to a greater extent than the moisture content, and drying produces a marked increase in MOR_H, which is offset by the development of drying-related defects. According to Freas (1995), such compensation is greater in low quality sawn timber and in pieces over 10 cm-thick. In addition, the lack of a significant relationship between mechanical performance and moisture content may have been due to the limited range of moisture content in the sample. The proposal of Green and Evans (1988) as regards distinguishing two groups of specimens (dry and moist) to assign different mechanical properties is not supported by the low effect of moisture observed in the present study.

The lack of any correlation between mechanical properties and moisture content may also be attributed to the heterogeneous distribution of moisture in the piece, in both axial and transversal directions. The moisture measured in beams is expressed as an average of the lowest moisture contents in the external fibers of the piece and higher moisture contents inside the piece. A piece with a low moisture content in the external fibers, those subject to the highest stresses, is more resistant than a piece with the same average moisture content but distributed homogeneously, in which the moisture content of the external fibers is similar to that in the center.

In the sample analyzed there was no significant correlation between density and MOR, although in structural specimens it is recommended that MOR is estimated, with density and MOE, as predictor variables (Castéra and Toratti 1999).

The proportion of sapwood did not affect either MOR or MOE but did have a significant effect on the type of failure, as already indicated.

The general or local grain slope did not have a significant effect on bending properties (MOR and MOE), although specimens with wavy fibers extended throughout the beam were very poor in terms of elasticity (MOE=7028 N mm^{-2} on average) and poor in terms of strength (MOR=43.1 N mm^{-2} on average).

In the sample analyzed there was a significant and inverse relationship between maximum knot size (on the edge) and both MOR and MOE (Table 3). However, the correlation was not high enough to justify construction of a predictive model of mechanical behavior based on maximum knot size in the piece. The distinction between knots depending on their position – face or edge – should be maintained in further studies as the influence on MOR and MOE is greater in edge knots (Table 3), and knots are more unfavorable the closer they are to edges (Courchene et al. 1998; Schaffer 1995).

The relationship between the two mechanical properties analyzed (MOR and MOE) was highly significant. The interest in MOE as a predictor of bending strength and other mechanical properties is largely based on the fact that MOE can be determined on the beam by different nondestructive methods such as measurement of static bending under low load conditions, dynamic bending vibration, or the dynamic longitudinal vibration. The aim of the graphical and statistical analyses of the plotted pairs (MOR versus MOE) was to construct a linear model, which is summarized in Table 4 and Fig. 3. Green and Evans (1988) reported a linear relationship between MOR and MOE for red oak, with R^2=0.46.

Fig. 3

As MOR is significantly correlated with the maximum diameter of edge knots and MOE, a stepwise regression method was carried out to identify the best explanatory variables for predicting MOR. The analysis revealed that only MOE can be included as a predictor variable of the modulus of rupture, thus excluding the variable related to the knot diameter, because it did not contribute significantly to improving the predictive value of the model. This was expected as the predictor variables tested were significantly correlated with each other (Table 3). The linear model proposed was:

$$MOR = 7.471 + 0.004MOE + \varepsilon \quad (3)$$

where MOR is the bending strength, modulus of rupture, in N mm^{-2} at a standard moisture content of 20%

MOE is the modulus of elasticity parallel to grain in N mm^{-2} at a standard moisture content of 20%

ε is the error term.

The regression Eq. (3) fitted was sufficiently valid because it was based on highly variable data (Table 1), and therefore the MOE values used for fitting represented most of the variability in the MOE of oak wood. There was a highly significant correlation between the square residual (ε^2) and ring width. A new linear model for predicting MOR was therefore fitted, but was restricted to beams of ring width < 5 mm. Considering this threshold for ring width, only 20% of the sample was rejected, but the error term decreased in absolute value from 9.9 N mm^{-2} to 8.6 N mm^{-2}. The regression constant in the new model was not significantly different from the null value (p=0.268) and the fitting was therefore carried out considering a null constant of regression:

$$\text{MOR} = 0.005\text{MOE} + \varepsilon' \qquad (4)$$

where MOR is the bending strength, modulus of rupture, in N mm^{-2}

MOE is the modulus of elasticity parallel to grain in N mm^{-2}

ε' is the error term.

The accuracy of model (4) was better than that of model (3) in terms of root mean square error ($RMSE$=17.8%), because most of the data contributing to the uncertainty in the prediction model (3) was removed, although the bias was higher (E=0.92%), and model (4) was finally rejected. Coefficients of determination were not used as criteria for comparing models because of the absence of constant of regression in Eq. (4).

In softwoods, in which the moisture content ranges from 10-20%, the relationship between MOE and MOR can be modelled by a complete parabolic equation in which parameters depend on the range of moisture (Evans et al. 1990). Nevertheless, in the present study the complete parabolic equation only improved the coefficient of determination up to R^2=0.71.

Conclusions

A single accurate model for predicting resistance to static bending in oak timber beams was developed on the basis of the modulus of elasticity, a predictor variable that can be obtained by nondestructive testing. The model provides consistent, logical estimates for a wide range of oak qualities because it was constructed with a sample with a highly variable number of external defects; the density exhibited the natural variability for the species and moisture was in the usual range considered for structural purposes.

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Table 1. Descriptive statistics for the variables obtained in bending tests carried out on structural oak beams (5×10×200 cm), in accordance with standard EN 408:2004 (European Committee for Standardization 2004b). Sample size: 66 specimens. *CV*: coefficient of variation. [a]: results converted to 20% moisture content.

Variable	Unit	Mean	Minimum	Maximum	*CV%*
Modulus of elasticity in bending [a]	N mm^{-2}	10022	2650	19077	37.7
Bending strength (MOR) [a]	N mm^{-2}	47.9	16.4	91.6	37.9
Moisture content	%	21	18	33	12.7
Apparent density	Kg m^{-3}	853	627	1051	9.0
Growth ring width	mm	3.5	0.8	7.5	47.5
Sapwood in cross-section	%	17.8	0.0	100.0	137.8
General slope of grain	%	3.7	0.0	24.7	143.5
Local slope of grain	%	18.5	0.0	54.2	70.4
Maximum face knot diameter	cm	3.4	0.0	9.5	66.0
Maximum edge knot diameter	cm	2.2	0.0	5.0	56.2
Maximum check length	cm	36	10	87	58.8
Maximum face wane width	cm	2.5	0.3	9.9	97.4
Maximum edge wane width	cm	1.9	0.3	5.0	70.1
Maximum wane length	cm	38	6	72	67.1
Bow	cm	1.3	0.3	6.0	136.7
Spring	cm	1.9	0.5	4.0	82.5
Twist	cm	0.9	0.2	3.0	103.7
Cup	cm	0.7	0.1	2.0	116.1

Table 2. Significance levels and F-values (*F*) in the one-factor analysis of variance for MOE, MOR, and the variable percentage of sapwood in the transverse section of the beam, with type of failure (i; ii) as a factor.

		Sum of squares	df	Square mean	*F*	Sig
MOE x	inter-group	9.533E7	1	9.533E7	7.347	0.009
type of failure	intra-group	8.304E8	64	1.298E7		
	total	9.257E8	65			
MOR x	inter-group	2533.6	1	2533.6	8.566	0.005
type of failure	intra-group	18929.9	64	295.8		
	total	21463.6	65			
sapwood x	inter-group	4163.2	1	4163.2	7.606	0.008
type of failure	intra-group	35029.7	64	547.3		
	total	39192.9	65			

Table 3. Partial matrix of correlation coefficients of Pearson *R* for variables analyzed in the oak beams in accordance with standard EN 408:2004 (European Committee for Standardization 2004b). MOR: modulus of rupture in bending at 20% moisture content; MOE: modulus of elasticity in bending at 20% moisture content; EKD: maximum edge knot diameter

	MOR	MOE	EKD
MOR	1		
MOE	0.84**	1	
EKD	-0.48**	-0.43**	1

** significant at $p \leq 0.010$.

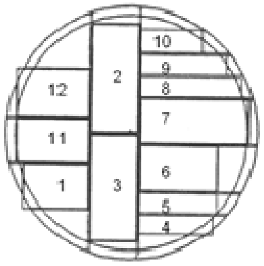
Table 4. Regression fitting of the linear equation MOR = a + b×MOE. R^2_{adj}=adjusted coefficient of determination; E=bias (%); $RMSE$=root mean square error (%)

Parameter	Coefficient	Significance level	Confidence interval for the coeff. (5% level of risk)		R^2_{adj}	E (%)	$RMSE$ (%)
			lower limit	upper limit			
a	7.471	0.037	0.447	14.495	0.70	0.71	20.9
b	0.004	0.000	0.003	0.005			

Fig. 1. Example of simplified radial sawing pattern, with two cutting lines and live sawing of the two half-logs. In this case, twelve sawn pieces were obtained, seven of which were of structural size

Fig. 2. Diagram of the test device for determining the modulus of elasticity in bending (MOE) and bending strength (MOR), in accordance with standard EN 408:2004 (European Committee for Standardization 2004b). F=test load; *h*=depth of piece (10 cm)

Fig. 3. Linear model fit for the mechanical variables obtained with oak timber in static bending tests. The dashed line represents the model fitted to the sample (Table 4) and white points represent the characteristic values of MOR and MOE for the strength classes defined for hardwoods in European standard EN 338:2003. Adapted from European Committee for Standardization (2003)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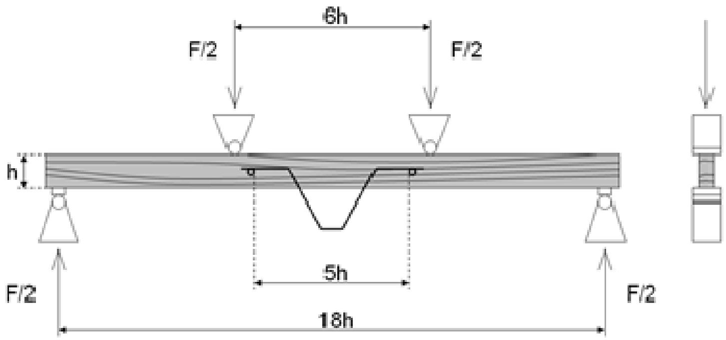
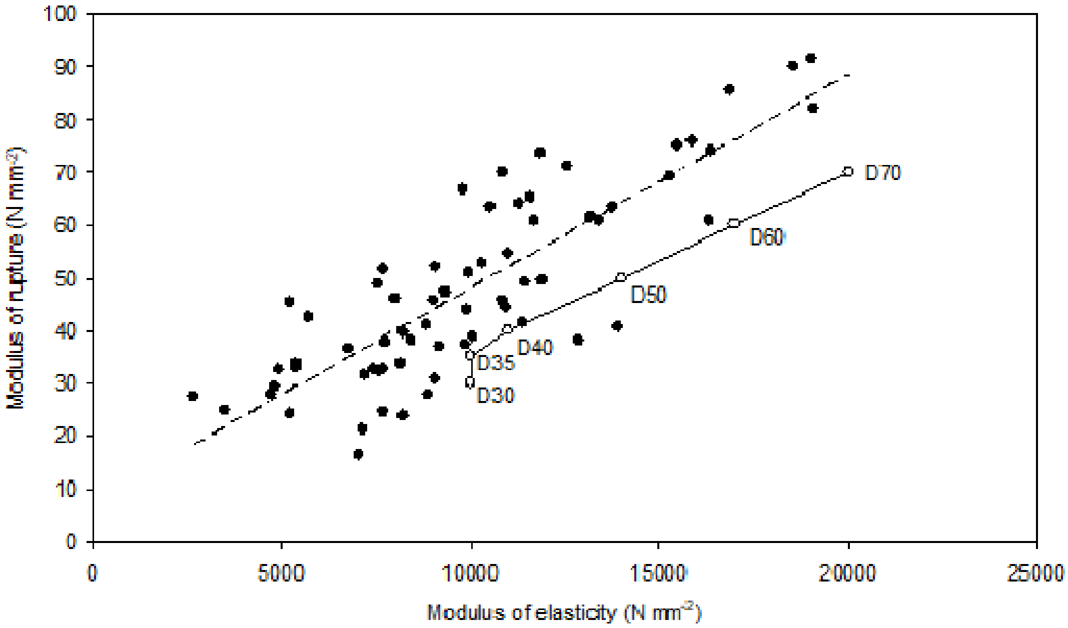
12
2
7
11
6
1
3
5
4


6h
F/2
F/2
h
5h
F/2
F/2
18h


Modulus of rupture (N mm⁻²)
Modulus of elasticity (N mm⁻²)
D70
D60
D50
D40
D35
D30
0
10
20
30
40
50
60
70
80
90
100
0
5000
10000
15000
20000
25000