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ABSTRACT

Wood is usually considered to be a material with equal stiffness in tension and compression. This supposition is not always supported by experimental evidence, however. Hardwoods appear to exhibit more evidence of bimodular behavior than softwoods, and it is hypothesized that wood structure or wood chemistry may be influential. Some data suggest that moisture content may affect tension and compression moduli differently. As it is most difficult to test individual fibers in compression, the question of whether bimodular behavior can be ascribed to fibers or only to solid wood remains unanswered. Some composite materials and synthetic fibers with known bimodular behavior were compared to wood and wood fibers in an attempt to better understand these issues.

Key Words: Young's modulus, moisture content, bimodular, mechanical properties, failure mechanisms, modulus of elasticity, tension, compression

Wood as a Bimodular Material

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Different strengths observed for wood in uniaxial tension and compression alert us to the different failure mechanisms for wood in uniaxial stress. Many consider it to be obvious that tensile properties are derived from the nearly longitudinal alignment of cellulose microfibrils in the cell wall; compression behavior, however, must be inherently more complex due to the potential for buckling of the lamellae towards the cell lumens. This may perhaps explain the different strength capacities in tension and compression; might the uniaxial Young's moduli (E) be affected as well?

One purpose of this paper is to review available data on uniaxial wood moduli. It appears to be commonly believed that the tensile and compressive moduli are equal, but it will be shown that there is insufficient consistent evidence in the literature to unequivocally support this belief. The (in-)equality of this relationship may be moisture dependent. Materials with known bimodular behavior will be compared to wood in an attempt to discern whether there are structural characteristics which might make bimodular behavior likely in wood.

REVIEW OF THE LITERATURE

Previous Determinations of Uniaxial Wood Moduli

The equality of Young's modulus in longitudinal tension and compression is often assumed (Ethington, 1961; Moe, 1961; Nwokoye, 1972; Anderson, 1981), but the assumption of moduli equality seems to be more firmly rooted in tradition than in factual evidence. Relatively few researchers have conducted tests to compare these values, and then usually at only one or two moisture contents. (No doubt this is partly due to the difficulty involved in machining and instrumenting tension specimens; compression samples are much more readily tested.) Data gathered by some researchers have led them to believe that negligible or only slight differences exist (Dietz, 1942; Sawada, 1958; Sliker, 1973, Bazan, 1980). Others, however, have concluded that there are significant differences between the moduli (Stern, 1944; Walker, 1961; Mazur, 1965; Zakic, 1976; Conners, 1985). Where available, data from these sources are presented in the following text and in Table 1; for convenience, all data have been converted to ratios of the Young's modulus in tension (E_t) to the Young's modulus in compression (E_c). The degree of departure from unity is used to compare these two values.

Reports of the Equality of Young's Moduli

Dietz (1942), Sawada (1958), Sliker (1973) and Bazan (1980) have published studies which conclude that there are minimal differences between E_c and E_t. Dietz conditioned and tested Douglas-fir samples at two moisture contents (MC), 9% and 24%. He also corrected each sample for small differences in density in an attempt to eliminate errors resulting from using unmatched specimens. Dietz found only minimal differences between moduli. Using his reported data, values for E_t/E_c have been calculated to be 1.035 and 1.028 at 9% and 24% MC, respectively.

Sawada (1956, 1958) collected tension and compression data from twelve woods with a moisture content range of 13 to 20 percent. Nine of these were tested at approximately the same MC in tension and compression; E_t/E_c ratios ranged from 0.884 to 1.187. Although the tensile moduli were generally higher than the compressive moduli, Sawada concluded that the differences were small and perhaps within experimental error.

Sliker (1973) worked with three species, but at essentially a single moisture content. His tests were conducted using the identical pieces of wood for several tests (bending followed by tension, then by compression). Red oak specimens were maintained at 11% MC, and western hemlock and Douglas-fir specimens were maintained at 13% MC. Sliker's data were not corrected for specific gravity differences among samples, and he reported that there were insignificant differences between the tensile and compressive longitudinal Young's moduli. Ratios of E_t/E_c calculated from his data range from 0.974 to 1.0.

Bazan (1980) tested different-sized eastern spruce and Douglas-fir beams with center and third-point loading conditions; most of his tests were conducted at 12% MC, with a few spruce beams tested at MCs between 15% and 20%. He stated that the modulus of elasticity in tension was usually about six percent greater than it was in compression. Bazan concluded that the observed differences were not significant, but he noted that they were slightly greater for beams at the higher moisture contents. Bazan's data were analyzed by the authors and are discussed in greater detail later in this paper.

Reports of the Inequality of Young's Moduli

Stern (1944) also examined the equality of the uniaxial moduli. He worked with yellow-poplar at 9% MC and found that the Young's moduli were significantly different; the ratio of E_t to E_c was 1.153 for sapwood and 1.101 for heartwood. Walker (1961) investigated the moduli of yellow-poplar as well, and concluded that the longitudinal modulus was greater in tension than in compression (E_t/E_c = 1.279) when the moduli were determined from uniaxial tests; the differences appeared to be substantially smaller when the moduli were determined from beam tests (E_t/E_c = 1.037). (Walker did not differentiate between heartwood and sapwood in his testing program). Later, Mazur (1965) used eastern spruce to determine the Young's moduli in uniaxially loaded specimens at 12% MC. His data indicate a value for E_t/E_c of 0.848. Mazur and Walker both thought that the unequal moduli resulted from localized differences in density within individual wood specimens (e.g., growth rings).

More recently, Zakic (1976) tested European poplar at 12% MC. Both compression and tension tests were performed on the same samples. Zakic did not indicate whether he corrected his moduli data for specific gravity variation among samples, but he found that the average Young's modulus in tension was nearly twice as high as the corresponding compression modulus (E_t/E_c = 1.930). This difference is far greater than others have reported.

The final data of which we are aware were collected by Conners (1985, 1988). Tension and compression data were collected from yellow-poplar specimens at four MC conditions: 6%, 12%, 18%, and green, defined by Conners as 25.6% based upon compression data trends. Approximately thirty sapwood specimens were divided between tension and compression tests for each moisture content. At 6% and 18% MC the tensile and compressive moduli could not be differentiated by statistical tests (E_t/E_c = 0.955 and 0.989, respectively), while at 12% MC the compressive modulus was greater (E_t/E_c = 0.840), and for green specimens the tensile modulus was greater (E_t/E_c = 1.171) (See Figure 1). Statistical tests did not indicate a significant relationship between specific gravity and the longitudinal moduli at each moisture content.

Analysis

There appears to be little agreement among these data regarding equality or inequality of the tensile or compressive moduli, even when the same species are studied. Stern and Conners, for example, both tested yellow-poplar, but Stern's data indicate that Young's modulus in tension should be higher at 9% MC; the trend indicated by Conners' data implies the reverse. Interestingly, Stern's sapwood tension values are very similar to those recorded by Conners for sapwood tension data, but the compression data are dissimilar.

Bazan's data were fairly extensive, and they were examined to determine whether more specific conclusions could be drawn from his observations. Analysis of his data by the authors appears to demonstrate a species effect as well as an effect due to the loading configuration. No statistically significant differences between E_t and E_c were detected for the Douglas-fir beams at 12% MC, but the spruce data were more complex. Examination of the tensile and compressive moduli for each beam test category (beam depth, moisture content and load configuration) showed that greater differences were usually observed under center loading conditions (see Table 2). For example, clear 2 x 6 spruce beams tested at 12% MC had an average E_t/E_c ratio of 1.026 under third-point loading, but an average E_t/E_c ratio of 1.083 under center loading conditions. The differences between the ratios at different load conditions were determined to be statistically significant, and the ratios were determined to be significantly different from unity using paired t-tests. The E_t/E_c ratio also increased with beam depth, perhaps more so for center loading conditions. As Bazan noted, higher moisture levels increased the disparity between E_t and E_c; 4 x 12 beams tested at about 17% MC had E_t/E_c ratios of 1.26 and 1.21 under third-point and center loading, respectively. Bazan's data were discarded from further evaluation in this paper due to questions about their value for our purposes.

The remainder of the data presented above represent only averages with unknown variability in most cases. Most investigators chose to test at only one or two moisture contents, and in most cases fewer than twelve specimens were tested in tension and compression at the same MC. With this in mind, the authors examined the available data to determine whether the average E_t/E_c ratio departed significantly from unity (see Figure 2). Walker's beam data were removed from the data set due to inconsistency of the experimental method with other investigations; also, Sawada had reported two sets of data for both sugi and apitong, and each pair of values was averaged for this analysis. Zakic's point for poplar was removed as an apparent outlier. A t-test of the remaining data showed that the average E_t/E_c value, 1.03, was not significantly different from unity at the 90% confidence level. Although there does not appear to be any evidence of bimodular behavior based upon the above analysis, the variability in the E_t/E_c ratios is rather striking. Hardwoods and softwoods were therefore analyzed separately to determine whether their mechanical responses were different. Hardwoods generally have an E_t/E_c ratio greater than or equal to unity and softwood ratios are more equally dispersed about 1.0. The average E_t/E_c ratio for these hardwood data was 1.05, with a range from 0.840 to 1.279 (Figure 3). This ratio was determined to be greater than zero with 90% confidence using a one-tailed t-test. Overall, hardwoods as a class seemed to be more variable than softwoods; this variability may be more important than the observed ratio.

As noted earlier, Conners' data indicate that very different trends can be recorded for Young's modulus in tension and compression at varying MCs, but not enough studies have been conducted to suggest whether similar observations might be expected with other species. More comprehensive testing of single species at differing moisture contents might be useful. Additional data may also result in the contradiction of the conclusions from the statistical analysis presented in the preceding paragraph.

We may speculate at this point whether the reported differences between compression and tension moduli are reproducible. Other materials are known to exhibit a bimodular behavior, however, so we must concede the possibility (if not the likelihood) of wood behaving in a similar fashion. In the following sections, we review some of the published information about bimodular materials and attempt to extend this knowledge to wood.

Table 1

Summary of comparable Young's moduli found in the literature

AUTHOR	MC%	COMMON NAME	SPECIES	$E_t/1.0x10^6$ psi	$E_c/1.0x10^6$ psi	E_t/E_c
Dietz	9	Douglas-fir	Pseudotsuga menziesii	2.050	1.980	1.035
Dietz	24	Douglas-fir	Pseudotsuga menziesii	1.830	1.780	1.028
Sawada	15	Sugi	Cryptomeria japonica	0.826	0.788	1.049
Sawada	16	Sugi	Cryptomeria japonica	0.907	1.027	0.884
Sawada	16	Obi-sugi	Cryptomeria japonica	0.842	0.761	1.107
Sawada	14	Yezo-matsu	Picea jezoensis	1.671	1.623	1.030
Sawada	13	Akamatsu	Pinus densiflora	1.264	1.198	1.056
Sawada	14	Buna	Fagus crenata	1.519	1.496	1.015
Sawada	14	Mizu-nara	Quercus crispula	1.708	1.724	0.991
Sawada	13	Keyaki	Zelkowa serrata	1.309	1.321	0.990
Sawada	14	Ichii-gashi	Quercus gilva	2.308	2.328	0.991
Sawada	14	Apitong	Dipterocarpus spp.	2.866	2.415	1.187
Sawada	13	Apitong	Dipterocarpus spp.	2.830	2.638	1.073
Stern	9	Yellow Poplar	Liriodendron tulipifera	1.869	1.621	1.153 S
Stern	9	Yellow Poplar	Liriodendron tulipifera	1.994	1.811	1.101 H
Mazur	12	Eastern Spruce	Picea spp.	1.510	1.780	0.848
Walker	6	Yellow Poplar	Liriodendron tulipifera	2.055	1.607	1.279 *
Walker	6	Yellow Poplar	Liriodendron tulipifera	2.438	2.352	1.037 **
Sliker	11	Red Oak	Quercus rubra	2.220	2.220	1.0
Sliker	13	Douglas-fir	Pseudotsuga menziesii	1.859	1.908	0.974

Sliker	13	Western Hemlock	Tsuga heterophylla	1.763	1.769	0.997
Zakic	12	Poplar	Populus euroamericana	2.740	1.420	1.930
Conners	6	Yellow Poplar	Liriodendron tulipifera	1.803	1.887	0.955 S
Conners	12	Yellow Poplar	Liriodendron tulipifera	1.838	2.187	0.840 S
Conners	18	Yellow Poplar	Liriodendron tulipifera	1.756	1.776	0.989 S
Conners	Green	Yellow Poplar	Liriodendron tulipifera	1.662	1.419	1.171 S

* = uniaxial test data, ** = bending test data

S = sapwood, H = heartwood

TABLE 2

Bazan's Data For Eastern Spruce Beams

Beam Size	M.C.%	Third-Point Loading Average E_t/E_c Ratio	Center Loading Average E_t/E_c Ratio
1.50 x 1.65	12	1.043	0.996
2 x 4 (nominal)	12%	0.997	1.074
2 x 6 "	12%	1.023	1.088
2 x 8 "	12%	1.047	1.126
4 x 12 "	15% to 18%	1.260	-
4 x 12 "	18% to 20%	-	1.209

Bimodularity of Fibrous Materials

The bimodularity of fibrous materials is considered in the following sub-sections. Reports of bimodularity in other materials are summarized here. Synthetic fibers and composites are next examined as model systems which might suggest possible mechanisms leading to bimodularity in wood. Wood is compared to the model systems in the final sub-section.

The Bimodularity of Synthetic Fibers and Composites

The bimodular behavior of various materials has been thoroughly documented in the past. As early as 1963, Clark showed that several composites consisting of rubber and either rayon, braided steel, or nylon cord exhibited significantly different moduli in compression and tension. Similarly, Patel, et al. (1976) found that composites of rubber and either polyester or aramid fibers displayed significant bimodular behavior (E_t/E_c = 59 for a polyester cord/rubber composite and 294 for an aramid cord/rubber composite); steel fiber-rubber composites did not display this effect to any significant extent. Other materials have likewise been shown to be bimodular, including other aramid composites (Zweben, 1978; Piggott and Harris, 1980), graphite composites (Jones and Nelson, 1976), porous stainless steel (Ducheyne et al., 1978), glass fibers in an epoxy matrix (Davis and Zurkowski), boron fibers in an epoxy matrix (Air Force Materials Lab, 1971), carbon fibers in a carbon matrix (Kratsch et al., 1972), granular ZTA graphite (Seldin, 1966) and granular ATJ-S graphite (Starrett and Pears, 1973). The E_t/E_c ratios for these and some other materials range from 1.2 to nearly 300, as documented in Table 3 (data from Zweben (1978), Jones (1977) and Bert (1979)). It is evident that a single explanation for bimodular behavior is not likely to accommodate the range of composition and structure displayed by the materials in this table.

Table 3

Tension and compression moduli data
for several different materials

Material	E_t/E_c Ratio
Aramid/Polyester	1.15
Glass/Epoxy	1.25
Boron/Epoxy	0.8
Graphite/Epoxy	1.4
Carbon/Carbon	2-5
ZTA Graphite	0.8
ATJ-S Graphite	1.2
Fabric/Rubber	2.6
Sintered, Porous Stainless Steel	10.0
Various Fabrics/Rubber	2-14
Polyester Cord/Rubber	59
Aramid Cord/Rubber	294
Rayon Cord/Rubber	278

MECHANISMS FOR BIMODULAR BEHAVIOR

Although the phenomenon of bimodularity has been observed for a number of materials (mostly fibrous), there have been few attempts to explain why some materials are bimodular. It appears that the mechanisms responsible for bimodularity are not well understood. Bert (1979) states that all of the mechanistic models for fibrous composites can be grouped into two classes, the "mean fiber angle" model and the "tie-bar/column on elastic foundation" model. These models account for bimodularity by assuming that there is some initial curvature in the fibrous reinforcement of some materials; the curvature disappears in tension, but it increases under compressive stress. As a result, tension moduli are observed to be greater than compression moduli. It has been shown that only small degrees of fiber curvature will result in significant differences between the tension and compression moduli (Herrmann et al., 1967). The models appear to implicitly assume that the matrix material is relatively flexible compared to the fiber. They fail to account for transverse shear deformations of the fibers and composites, however, and cannot account for bimodularity of porous stainless steels or other non-fibrous materials.

Some materials, such as aramid fibers, may be bimodular because of their chemical structure (molecular conformation). Aramid is an aromatic polyamide [poly(p-phenylene terephthalamide)], also known by the Du Pont trade name of Kevlar; it is of particular interest here because of the similarities between its polymeric structure and that of cellulose. Cellulose microfibrils and aramid fibers are both composed of polymeric chains, with strong covalent bonds between monomeric units along the chain axis and hydrogen bonding between the chains (Winandy and Rowell, 1984; Northolt, 1974).

Greenwood and Rose (1974) found differences in the ultimate compressive and tensile strength of aramid composites and concluded that these differences resulted from unlike modes of aramid fiber deformation in tension and compression. They believed that tensile deformation resulted from elastically extending the polymer backbone, and compression deformation was attributed to molecular delamination between the weakly-hydrogen bonded polymer chains. Photomicrographs appear in the literature depicting this phenomenon, which in a compressively-stressed fiber appears as a series of kinked bands (Greenwood and Rose, 1974; Lafitte and Bunsell, 1982; Davidovitz et al., 1984). This mode of compressive strain has also been shown for wood (Keith and Cote, 1968; Dinwoodie, 1968) and other systems including polyethylene (Holland and Black, 1979; Kolbeck and Uhlmann, 1976) and graphite (Jones and Johnson, 1971). Data are unavailable for the compressive stiffness of aramid fibers, but Greenwood and Rose stated that they did not believe that Kevlar 49 fibers were elastic in compression. It would seem reasonable that different deformation mechanisms in tension and compression would lead to differences in the observed moduli.

Bimodularity has also been observed in fibrous composites made from fibers with little inherent compressive stiffness except that obtained from the restraint of the surrounding matrix (Tabbador, 1979). Tabbador, writing about cord-reinforced rubber composites, stated that the "reinforcing elements are one dimensional structural members with high tensile stiffness but low compressive resistance when not laterally restrained. These cords, however, attain appreciable stiffness when embedded in a matrix which provides lateral support. The apparent compressive stiffness of such composites is therefore less than that of tensile stiffness, as a consequence of micro-buckling response of the cords to compressive forces. This concept has been applied to explain the smaller elastic modulus in longitudinal compression than in tension in the same direction." This analysis would suggest that the failure mechanisms of reinforcement fibers should be different in tension and compression. As noted above, both wood and other fibers, especially aramid fibers, are documented to fail through kink initiation under compressive stress. Woody fibers have brittle failures in tension; kink initiation is a physical impossibility under tension.

Potential Mechanisms for Bimodular Behavior of Wood

There are two separate types of bimodular behavior which require explanation: 1) bimodularity appears to be more commonly observed in hardwoods; 2) bimodularity may be moisture-dependent. Each of these will be discussed in turn.

Moisture-independent bimodularity

On a gross level, fibers must often have some initial curvature because of displacement by wood rays, etc. Therefore, the "mean fiber angle" or the "tie-bar/column on elastic foundation" models might be useful in understanding why wood sometimes appears to be bimodular. Perhaps hardwoods are affected more because their fibers are shorter and consequently perturbed along a greater proportion of their length, or perhaps hardwoods are affected more because they generally have a greater proportion of rays compared to softwoods (Panshin and de Zeeuw, 1980). Dinwoodie (1968) has also shown that the kink bands noted earlier occur predominantly around ray cells and especially at the outer rays. Tabbador's explanation of bimodular behavior might also be appropriately applied, as wood fibers are essentially limp when removed from the encrusting lignin/hemicellulose matrix by chemical maceration.

On a finer scale, bimodularity might be attributed to the different modes of strain in compression as compared to tension. There is evidence to suggest that wood deforms in both compression and tension in ways similar to Kevlar. Studies have shown that wood compression produces both kink bands and pleated regions in compressed fibers (Keith and Cote, 1968; Dinwoodie, 1968). Mark has described the behavior of wood in uniaxial tension as displaying elastic behavior (Mark, 1972). Furthermore, he describes cellulose as it exists in the microfibril as also behaving elastically in tension. Page, et al. (1971), showed that individual kraft pulp fibers displayed elastic behavior in tension up to about 40% strain and could afterwards collapse and twist. Extending the analogy of aramid fibers to wood, it seems possible that wood deforms in compression through delamination while it deforms in tension by axial extension of the cellulosic polymer chains. The delamination would occur by the breaking of hydrogen bonds either between cellulosic chains, micelles, or microfibrils.

Whether wood (as a fibrous composite) is the bimodular material, or whether the individual wood fibers have intrinsic bimodular characteristics is unknown. Both conjectures may be correct. Because wood fibers are so troublesome to test in compression, it is difficult to answer this question at the present time.

Moisture-dependent bimodularity

None of the mechanisms noted in the previous section would seem to have relevance to discussions of moisture-related bimodular observations. We can only speculate about the reasons for Conners' observations; based upon data in the literature (Cousins, 1976, 1978; Salmen, 1982) it seems likely that the essentially unchanging tensile moduli are due to the crystalline cellulose component (shown to be relatively insensitive to moisture penetration according to Salmen). Compression stiffness is more sensitive to moisture, and may be due to softening of amorphous cellulose, hemicelluloses, and (to a lesser extent), lignin.

It is interesting that Conners' data appear to demonstrate that bimodular behavior may be affected by the choice of moisture content for testing. It is possible that previous tests of some woods have not detected bimodularity for this reason. Conners' data at 12% MC are not consistent with data collected by Sawada near this MC, however, and we cannot as yet explain why different species appear to be affected in different ways. Perhaps significant differences among species with respect to hemicellulose and lignin type, concentration and placement can affect mechanical property observations in this manner.

SUMMARY

There appears to be sufficient evidence to show that some woods may have different Young's moduli in tension and compression. On average, hardwoods are reported to have a tension modulus which is about 5% greater than the compression modulus, but this is perhaps of less significance than the variability among the data reported in the literature. Softwoods do not appear to have significantly different moduli. Measurements collected from uniaxial testing may be more reliable than data from beam tests, as at least one researcher's data appear to have been affected by beam depth and loading configuration. It is inferred from studies of engineered materials with known bimodular behavior that bimodular behavior in wood may be due to fiber curvature induced by ray contact.

Moisture content has been shown to affect compressive moduli less than tensile moduli, and it seems likely that this is due to varying hygroplasticization effects on the various wood components. Moisture content may affect observations performed to detect bimodular behavior, but little consistency is apparent among the limited data available. Perhaps there are some species-specific effects due to differences in types and placement of hemicelluloses and lignins. Further study is warranted in this area.

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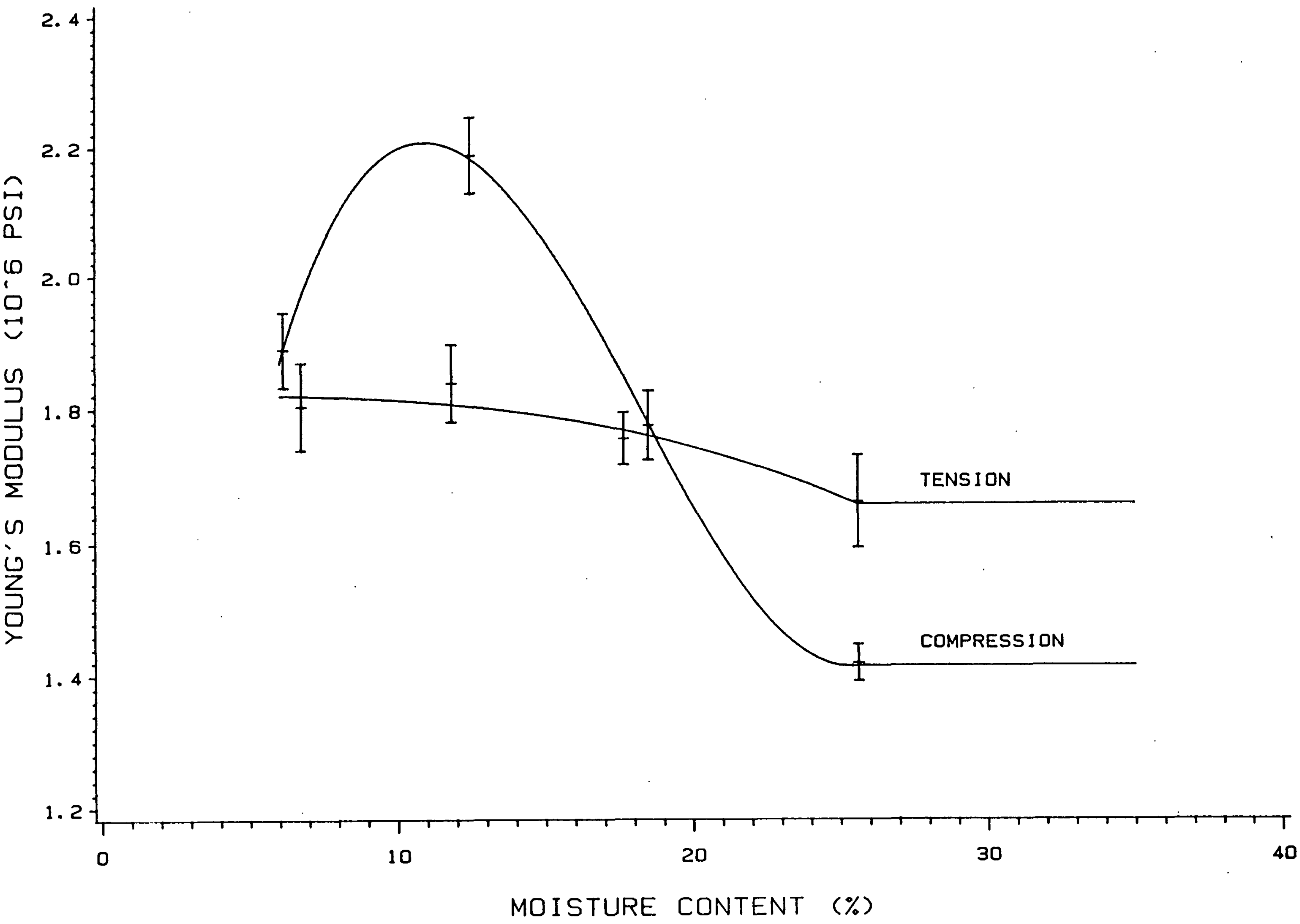
CAPTIONS

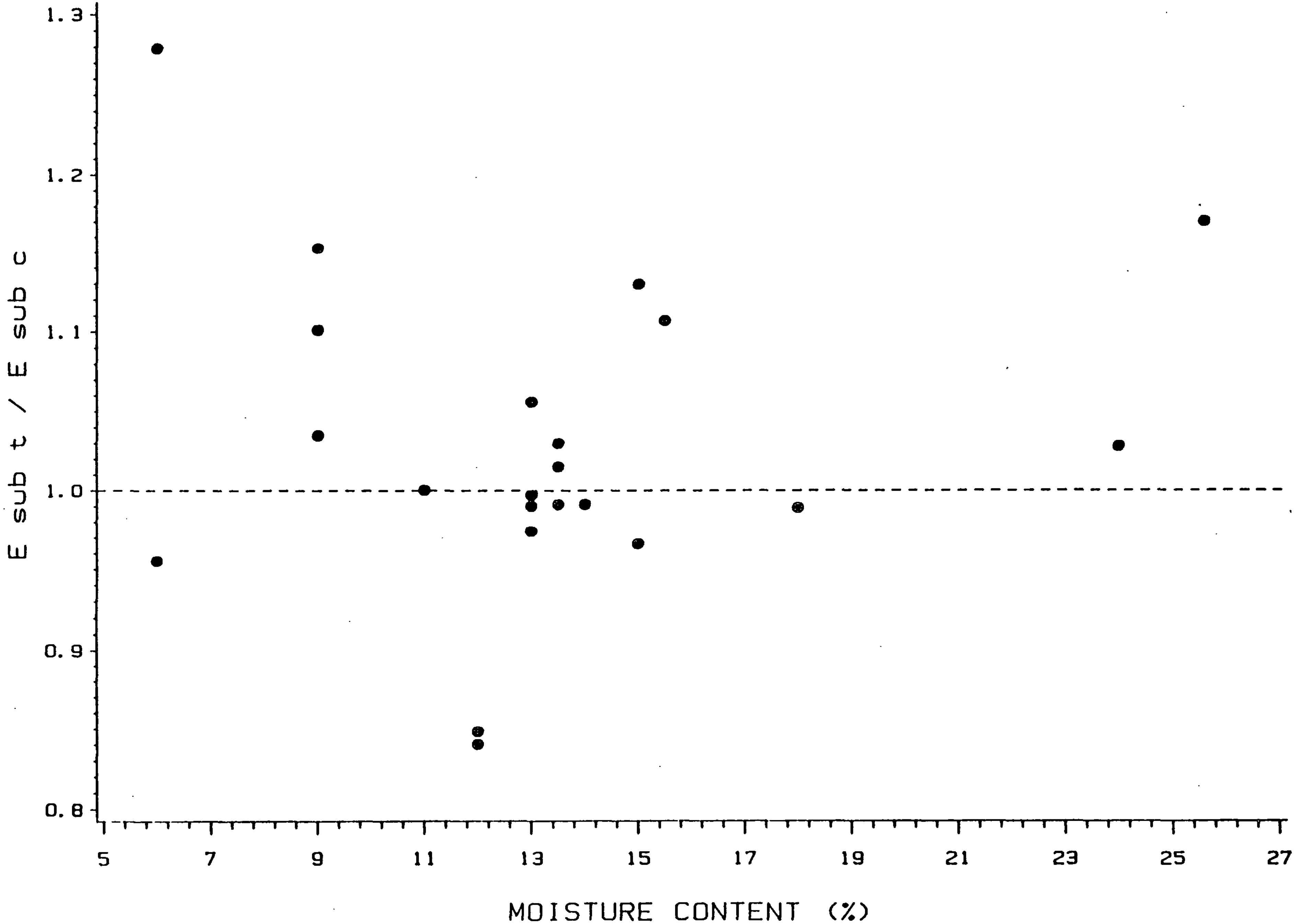
Figure 1: Conners' data (1985) for uniaxial moduli of yellow poplar. Green moisture content was defined to be 25.6 %. Bars indicate means and +/- one standard error of the mean; lines shown are predictive models for data.

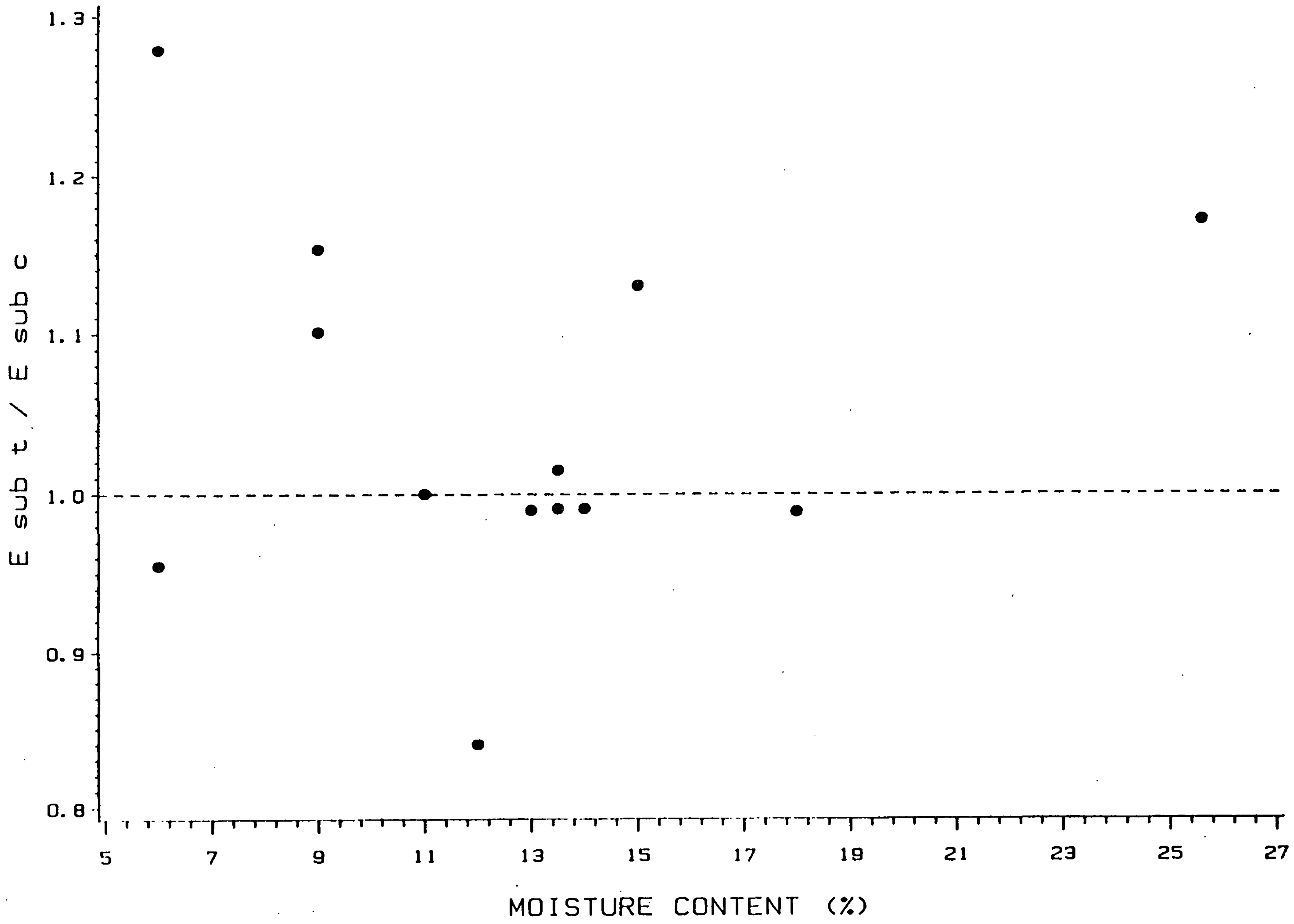
Figure 2: E_t/E_c data from Table 1 plotted as a function of moisture content. Dotted line represents equality of tension and compression moduli.

Figure 3: E_t/E_c data from Table 1 plotted as a function of moisture content. Hardwood data only.



YOUNG'S MODULUS (10^6 PSI)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
0
10
20
30
40
MOISTURE CONTENT (%)
TENSION
COMPRESSION


1.3
1.2
1.1
1.0
0.9
0.8
E sub t / E sub c
5
7
9
11
13
15
17
19
21
23
25
27
MOISTURE CONTENT (%)


1.3
1.2
1.1
1.0
0.9
0.8
E sub t / E sub c
5
7
9
11
13
15
17
19
21
23
25
27
MOISTURE CONTENT (%)