Abstract

A pin-injecting Pilodyn and a James V-meter stress-wave measuring instrument were used to estimate crushing strength and modulus of elasticity (MOE) of mine props. Both nondestructive testing instruments can be used to sort or grade mine props. The timber sampling included 26 species or species groupings ranging from spruce and aspen to oak and hickory. Test material was selected to include a wide range of decay levels. Dynamic MOE derived from stress-wave measurements generally gave the best estimates of crushing strength and static MOE for samplings of all species combined, hardwoods only, softwoods only, and sorts of maples, oaks, and pines. Results indicate that species-independent machine stress-rating systems can be a viable supplement or alternative to visual grading.

Commercial machine stress rating of lumber (MSR) began in the United States about 20 years ago using the relationship between strength and stiffness as a stress-rating criteria. In U.S. markets, MSR is not used for sorting wide mixes of species into a few grades but rather as a precision sorter of a few species for highly specialized markets.

In 1979, a relationship between modulus of elasticity (MOE) and modulus of rupture (MOR) was demonstrated (16) for three Brazilian hardwoods, and MSR concepts were concluded to be applicable to these tropical hardwoods. MSR was also suggested as the possible key to efficient utilization for structural application of a large, undescribed forest resource consisting of many species. That principle, however, has not yet been demonstrated.

This report assesses the viability of two nondestructive devices, the Pilodyn and James Electronics V-meter, for sorting or grading groups of mine timbers with and without species identification. The results suggest that species-independent stress grading could have application not only to wood products from mixed woodlands of temperate regions but to the highly heterogeneous timber resources of the lowland tropics.

Materials and methods

Decayed and sound mine props were collected from 17 coal mine sites extending from Pennsylvania westward to Utah. As this material was accumulated, it was placed in cold storage (36°F, 82% relative humidity (RH)) to minimize further biodegradation and possible changes in physical and mechanical properties. Field measurements showed that most of the mine timbers had an "in-place" moisture content (MC) that ranged from 20 to 30 percent.

The 329 timbers sampled consisted of 26 species or species groupings including such low-density, low-strength woods as spruce, fir, aspen, and sassafras as well as the heavier, high-strength hickory, black locust, and oak. Twenty species were hardwoods, represented by 212 mine timbers; 6 were softwoods, represented by 324 timbers.

The Pilodyn is a device that fires a calibrated spring-loaded pin into wood and measures the depth of penetration.

The use of trade, firm, or corporation names is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval of any product by the U.S. Dept. of Agriculture to the exclusion of others which may be suitable.

The authors are, respectively, Research Forest Products Technologist, Supervisory Research Plant Pathologist, and Research Forester, USDA Forest Serv., Forest Prod. Lab., P.O. Box 5130, Madison, WI 53705. Funding for this study was provided by the U.S. Bureau of Mines. For more information, see W. Eslyn, Decay in mine timbers. Part I. Sampling procedures and conditions and description of samples, Forest Prod. J. 33(6):27-30; and W. Eslyn and F. Lombard, Decay in mine timbers. Part II. Basidiomycetes associated with decay of coal mine timbers, Forest Prod. J. 33(7-8):19-23. This paper was received for publication in December 1982.


117 mine timbers. The best represented hardwoods were 48 timbers of white oak, 43 of red oak, and 31 of soft maple. The best represented softwoods were 65 timbers of lodgepole pine and 36 of southern pine.

Most of the timbers (91%) were in the round with top diameters 4 to 8 inches and end trimmed to 3-foot lengths. They were selected to represent a wide array of decay levels: about 40 percent had little or no decay, 10 percent had advanced decay, and the remainder were at some intermediate level. This sampling mix of species and decay level is indeed a challenge for any nondestructive devices used as strength predictors.

**Nondestructive tests**

**Pilodyn.** - This newly developed instrument releases a spring-loaded pin into the side grain of wood using a constant amount of energy (Fig. 1). The depth of pin penetration is reported to reflect a complex mixture of tension and compression properties parallel and perpendicular to the grain (9). A “single shot” 18J instrument, with a blunt-ended pin 2.5 mm in diameter and 90 mm long, was used. Depth of pin penetration is read directly off a scale on the instrument.

Three pairs of diametrically opposed in-line measurements were made normal to the longitudinal axis of each mine timber, at midlength and 10 inches above and below midlength. Measuring stations were positioned to avoid knots, checks, and splits. An average penetration value was then calculated for each piece.

**Stress-wave measurements.** - A James Electronics V-meter with 54-kilohertz (kHz) flat transducers (Fig. 1) was used to measure sound wave transit time. This is an ultrasonic nondestructive testing device that measures the time required for mechanical energy, in the form of pulsed sound waves, to move through a material.

Velocity (C) of the pulsed sound waves equals path length (in.) divided by transit time ( microseconds). Dynamic MOE (psi) was calculated by

\[
MOE = \frac{C^2 p}{386.4 \text{ in./sec/sec}}
\]

where \( p \) is the density, including moisture, of the test material in pounds per cubic inch.

Transit times parallel to the grain were measured by placing the transducers on opposite ends of the shortened 3-foot mine props. To facilitate contact, a heavy grease couplant was used between the transducers and the test specimens.

In the initial plan for this study, sound wave measurements were to be made across-the-grain only. After testing was underway, it was decided to include parallel-to-grain measurements as well. This accounts for most of the sample size discrepancies (Table 1). Sound wave measurements across-the-grain correlated rather poorly with mine timber properties (5) and these results are not included in this report.

**Destructive tests**

**Compression parallel to the grain.** - Methods described in ASTM designation D 198-76 (1) were used to determine crushing strength and MOE of the 3-foot timber lengths. To assure an \( l/r < 17 \) specified for a short column (\( l = \) column length, \( r = \) radius of gyration), lateral supports were used at midlength. Before testing, MCs were measured with a resistance type meter. Also, the timbers were measured as needed for stress calculations and banded on the ends with steel straps to prevent brooming during loading. Specimens were centered between rocker-type bearing blocks in a static testing machine and loaded at a fiber strain rate of 0.003 inch/inch per minute (three times the standard rate) to reduce testing time for the large number of specimens. Deformations were measured over a 20-inch span using paired linear variable displacement transducers (LVDTs).

**Results**

To statistically correlate stress-wave and Pilodyn measurements with timber properties, data were pooled as follows: 1) all species combined, 2) hardwoods only, 3) softwoods only, 4) soft maples, 5) white oaks, 6) red oaks, 7) southern pines, and 8) lodgepole pine. The three hardwood groups, the southern pines, and lodgepole pine represented 68 percent of the test samples.

Table 1 shows mean, standard deviation, and sample size for the density measurements, Pilodyn penetrations, maximum crushing strength, and static and dynamic MOE determinations for all timbers combined, hardwoods only, softwoods only, and the five selected species or species groups.

**Physical properties of mine timbers**

**Moisture content.** - At time of test, 95 percent of the mine timbers had less than 35 percent MC. For 78 percent, MC was 25±5 percent. Timbers with less than 15 percent MC were mostly lodgepole pine and Engelmann spruce from a Colorado coal mine.

**Density.** - For all species combined, at all levels of decay and at all the levels of MC, the average density was 37 pcf. The 255 test timbers with MCs between 20 and 30 percent also averaged about 37 pcf. Similarly, for
this narrower MC range, there was little or no difference in average density between the hardwoods only, softwoods only, and the other species groupings. Density ranged from 15 pcf for a very heavily decayed aspen specimen to 65 pcf for rock elm free of decay.

**Pilodyn penetrations**

Pilodyn pin penetrations ranged from 10 to 70 mm. Both extremues were measured in white oak, one sound and the other severely decayed. Mean penetration ranged from 34 mm for the low-density lodgepole pine to 25 mm for the heavier white and red oak groups.

**Dynamic MOE**

The dynamic MOE parallel to the grain (derived from stress-wave velocity measurements) of individual members ranged from 200,000 to 3,200,000 psi, averaging 1,594,000 psi for all species combined (Table 1).

**Static tests - compression**

**Maximum crushing strength.** - To minimize the influence of variable MCs on crushing strength and on static MOE values, these properties were adjusted (14) to a green MC of 25 percent. It was assumed that moisture-strength adjustments for mine timbers, particularly for round ones, would be similar to those developed for small clear specimens. Most of the needed adjustments were for timber specimens having MCs within 5 percent of the assumed “green” value of 25 percent. Only 40 timbers had MCs of less than 20 percent.

The adjusted green strength in compression parallel to the grain, based on the static tests of all mine timbers, ranged from 500 to 5,000 psi, averaging 2,110 psi (Table 1).

**Static MOE.** - Adjusted for MC, individual static MOE’ values ranged from 200,000 to 2,600,000 psi, averaging 1,064,000 psi for all species combined (Table 1).

**Regression analyses**

Regression analyses were used to show how well Pilodyn penetration correlated with density, maximum crushing strength, and static MOE for the various species and species groups. Predictability of timber properties was also determined using dynamic MOE derived from V-meter stress-wave velocities. Regression analyses were also used to show correlations with visual estimates of decay levels in the timbers. In most of the latter cases, R² (coefficient of determination) was poor and these results are not presented here. However, the effects of decay fungi are assessed indirectly by the crushing strength and static MOE measurements.

Scatter diagrams were used to determine whether linear or curvilinear regression analysis was appropriate. It was judged that relationships involving Pilodyn penetrations were best described by curvilinear analysis - those involving dynamic MOE by linear analysis. Transformation to log Y (base e) was used to fit the curvilinear data (log Y = a + bX where X is Pilodyn penetration and Y is either density, maximum crushing strength, or static MOE). Coefficients of determination and regression equations are given in Table 2. Discussion of these results follows.

**Pilodyn (18J-2.5 mm) penetration as a correlator with**

**Density.** - The R² was 0.58 for all species combined, 0.70 for all hardwoods combined, and ranged from about 0.6 to 0.8 for the three hardwood species groups. Pilodyn pin penetrations as a predictor of den-
TABLE 2. Coefficients of determination ($R^2$) and Coefficients ($a$ and $b$) in regressions of Pilodyn and V-meter stress-wave measurements versus density, crushing strength, and modulus of elasticity of various mine timber populations.

<table>
<thead>
<tr>
<th>Species groupings</th>
<th>Density $a$</th>
<th>Density $b$</th>
<th>Maximum crushing strength $a$</th>
<th>Maximum crushing strength $b$</th>
<th>Static MOE $a$</th>
<th>Static MOE $b$</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All species</td>
<td>4.10</td>
<td>.0174</td>
<td>0.58</td>
<td>8.72</td>
<td>.0403</td>
<td>0.61</td>
<td>7.75</td>
</tr>
<tr>
<td>Hardwoods only</td>
<td>4.18</td>
<td>.0186</td>
<td>0.70</td>
<td>8.76</td>
<td>.0438</td>
<td>0.67</td>
<td>7.83</td>
</tr>
<tr>
<td>Softwoods only</td>
<td>3.68</td>
<td>.00070</td>
<td>0.56</td>
<td>8.68</td>
<td>.0360</td>
<td>0.50</td>
<td>7.61</td>
</tr>
<tr>
<td>Soft maple</td>
<td>3.97</td>
<td>.0138</td>
<td>0.76</td>
<td>8.80</td>
<td>.0424</td>
<td>0.75</td>
<td>8.25</td>
</tr>
<tr>
<td>White oak</td>
<td>4.22</td>
<td>.0166</td>
<td>0.64</td>
<td>8.92</td>
<td>.0531</td>
<td>0.73</td>
<td>7.93</td>
</tr>
<tr>
<td>Red oak</td>
<td>4.14</td>
<td>.0161</td>
<td>0.69</td>
<td>8.83</td>
<td>.0458</td>
<td>0.73</td>
<td>7.94</td>
</tr>
<tr>
<td>Southern pine</td>
<td>3.78</td>
<td>.0079</td>
<td>0.10</td>
<td>8.53</td>
<td>.0256</td>
<td>0.42</td>
<td>7.61</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>3.59</td>
<td>.0044</td>
<td>0.11</td>
<td>8.52</td>
<td>.0321</td>
<td>0.42</td>
<td>7.51</td>
</tr>
</tbody>
</table>

For Pilodyn, the regressing Log e $Y = a + bx$ where X is the Pilodyn measurement (mm) and Y is either density (pcf), crushing strength (psi), or static modulus of elasticity (1,000 psi); for the V-meter, the regression is $Y = a + bx$ where X is dynamic modulus of elasticity (1,000 psi), and Y is either crushing strength (psi) or static modulus of elasticity (1,000 psi).

Maximum crushing strength. - The $R^2$ for the curvilinear relationship between Pilodyn and maximum crushing strength was 0.61 for all species combined, 0.67 for hardwoods combined, and 0.50 for softwoods combined. Again, the individual species of pine had the poorest coefficients of determination (0.42), but those of the maple and oak sorts were about 0.75.

In these regressions, maximum crushing strengths were adjusted to 25 percent MC, but the Pilodyn penetrations were not. Corrections were made for these MC differences, as described above, and new regressions calculated for the pines; there was no improvement in the correlation.

An 18J Pilodyn was used (11) with a 3-mm-diameter pin penetration to predict tensile strength of European whitewood (Picea abies) lumber. That study obtained an $R^2$ of 0.48 for the higher grades (S10), about the same goodness of fit obtained with the coniferous mine timbers loaded in compression in this study.

Static MOE. —The $R^2$ was only 0.38 for all species combined and a low of 0.24 for all softwoods combined. Again, the Pilodyn was most effective with hardwoods: $R^2$ of 0.50 for all hardwoods combined, 0.74 for the maples, and 0.64 for each of the oak groups. The $R^2$ for the southern pines and lodgepole pine separately was less than 0.2. There was no improvement in the correlations if Pilodyn penetrations were corrected for MC differences.

Parallel-to-grain dynamic MOE as a correlator with:

Maximum crushing strength. - Dynamic MOE parallel to the grain had good linear correlation with crushing strength (Table 2). All species combined, hardwoods combined, maple, and the two oak groups had an $R^2$ that ranged from 0.72 to 0.87. The softwoods combined and southern pines and lodgepole pine separately had an $R^2$ of 0.47 to 0.52.

Sities for softwoods were poor with $R^2$ less than 0.2. This may be partially attributed to the lower variability in the softwood as the coefficients of variation for Pilodyn measurements in softwoods are considerably lower than the hardwoods.

Other assessments of density using the Pilodyn have mixed results. A 12J Pilodyn with a 2.5-mm-diameter pin, used to detect loss in density due to attack by soft-rot fungi in eucalyptus poles, obtained an $R^2$ less than 0.2 for both aboveground and belowground assessments (13). Other regressions (9) of Pilodyn penetration on ovendry density gave an $R^2$ of about 0.8 to 0.9 for mixes of species but 0.49 for pine alone and 0.60 for spruce alone. For all species combined, a hyperbolic model gave a better fit than a straight-line model. Results of tests using the Pilodyn as a predictor of ovendry specific gravity of eucalyptus (10) obtained an $R^2$ of about 0.90. Using the Pilodyn to assess basic density in standing radiata pine trees resulted in an $R^2$ of 0.92 (6) and an $R^2$ of about 0.66 for live plantation-grown loblolly pine (17).

We obtained very low $R^2$ for southern pines and lodgepole pine, compared to other reported results (6, 9, 10, 17), due possibly to the low variability in mechanical properties.

In one study (9), using a mix of species, below the fiber saturation point a 10 percent MC increase resulted in a 10 percent increase in pin penetration. Our Pilodyn penetrations for both the southern pines and lodgepole pine were thus adjusted to a uniform green MC and $R^2$ values were recalculated. For both species there was no improvement in the correlation. However, our density measurements were also influenced by a range of MC.

To determine if this was a major influence, softwood mine timbers were chosen within the narrow range of 25±5 percent MC. For this more homogeneous grouping, $R^2$ improved from 0.1 to 0.3, still far from the values reported in the literature.
Static MOE. - Here too, there was an excellent linear relationship with a high $R^2$ of 0.71 to 0.94 for all species combined, for hardwoods only combined, and for the maple and the two oaks separately (Table 2). The $R^2$ for softwoods combined and for the southern pines and lodgepole pine separately ranged from 0.54 to 0.66.

Parallel-to-the-grain stress-wave velocity measurements were made on the mine timbers in the “as is” MC condition. In sweetgum studies (8), stress-wave velocity and calculated dynamic MOE parallel to the grain had both decreased as MC increased to about 35 percent. Within this range, for each 5 percent increase in MC there had been a 2 to 3 percent decrease in stress-wave velocity and a 2 to 3 percent decrease in dynamic MOE. In pine studies (4), stress-wave velocity had decreased with MC increases to about 30 percent MC, with about the same rate of decrease as in the sweetgum studies. When red pine, maple, and Douglas-fir were measured for variations, with changes in MC, of ultrasonic transit time parallel to the grain (12), a 3 percent decrease in velocity again had been observed for every 5 percent increase in MC.

Because of the moisture effect observed in the literature, the dynamic MOE values for southern pines and lodgepole pine were adjusted to 20 percent MC (4, 8, 12). There was no improvement in the correlations.

Stress-wave velocity ($C$) measurements were also correlated with static MOE and crushing strength. In almost all cases these correlations were poorer than those obtained using the derived dynamic MOE. These results are reported elsewhere (5).

Discussion

In a quality inspection system, standards can be set so low that all items inspected are accepted or so high that all are rejected. Obviously a compromise must be made to reach some acceptable balance between efficient resource use, economy, and safety.

If $R^2$ approaches unity, regression lines can be used directly to reject all material with a strength property less than some minimum allowable stress. But correlations rarely approach unity. Because of scatter of individual values in typical strength prediction relationships for wood, a system using the regression line will accept many timbers with less than desirable properties; many with acceptable properties will be rejected.

Procedures developed to take this variability into account when deriving allowable stresses for structural lumber by MSR (3, 7) can guide development of allowable unit stresses for mine timbers based on the Pilodyn and stress-wave MOE obtained in this study.

Allowable stress in compression ($F_c$)

A schematic procedure for selecting a level of Pilodyn penetration or dynamic MOE (sorting parameters) to obtain an acceptable strength level in compression parallel to the grain is demonstrated in Figure 2. A simple linear regression line relating the prediction parameter to the strength property (log strength in the case of Pilodyn) is fitted to the data for a population of interest, e.g., all hardwoods combined. Variability in the prediction model is accounted for by using a lower confidence line that assures that about 95 percent of all data will be above this line and about 5 percent of the material will have strength properties less than predicted.

In typical MSR grading systems, lumber is sorted into two or three strength-stiffness grade classes depending upon marketing considerations. In the case of mine timbers, we only wish to determine if individual pieces have an acceptable strength. Once an acceptable strength level has been established and its predictor determined, the grading model divides a timber population into two categories: one having adequate strength and the other inadequate strength. Each category contains timbers that are either correctly or incorrectly sorted.

In Figure 2, the timbers (mine timbers in our case) in quadrants I and III are sorted correctly and those in II and IV are sorted incorrectly. Those in quadrant IV present no problem other than one of wasteful rejection of material with adequate strength. Those in quadrant II do present a problem in that material is accepted even though its strength is less than the desired level. Note, however, that use of the lower confidence tends to minimize the material in this category (shaded area, Fig. 2).

The effectiveness of the assessment system can be judged by counting the number of timbers falling into each of the four categories. The nondestructive test and associated screening model that sorts the largest number of mine props, for any population, into categories I (accepted correctly) and III (rejected correctly) and the smallest into categories II (accepted incorrectly) and IV (rejected incorrectly), particularly into category 11, is most desired.

Table 3 gives the category proportions for all species combined, all hardwoods combined, and all softwoods combined using Pilodyn and dynamic MOE as

![Figure 2. A schematic sort using a nondestructive predictor based on a lower confidence line for the prediction model.](Image)
TABLE 3. Numbers of mine timbers sorted into four accept-reject categories by two nondestructive test measurements assuming an allowable compression parallel-to-the-grain stress \((F_c)\) of 400 psi.

<table>
<thead>
<tr>
<th>Species grouping</th>
<th>(n^a)</th>
<th>Accepted correctly category I</th>
<th>Accepted incorrectly category II</th>
<th>Rejected correctly category III</th>
<th>Rejected incorrectly category IV</th>
<th>Percent correct (^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All species</td>
<td>929</td>
<td>257</td>
<td>1</td>
<td>40</td>
<td>86</td>
<td></td>
</tr>
<tr>
<td>All hardwoods</td>
<td>212</td>
<td>156</td>
<td>4</td>
<td>22</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>All softwoods</td>
<td>117</td>
<td>101</td>
<td>1</td>
<td>5</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>DYNAMIC MOE PARALLEL TO GRAIN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All species</td>
<td>285</td>
<td>189</td>
<td>1</td>
<td>34</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>All hardwoods</td>
<td>151</td>
<td>101</td>
<td>1</td>
<td>26</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>All softwoods</td>
<td>114</td>
<td>94</td>
<td>0</td>
<td>4</td>
<td>16</td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\)Sample size \(n = \sum\) of categories I, II, III, and IV.

\(^{b}\)Sum of categories I and II divided by \(n \times 100\).

predictors of crushing strength. An assumed allowable \(F_c\) of 400 psi is used throughout.\(^3\)

Dynamic MOE was more effective than Pilodyn penetrations for sorting mine timbers to minimize the number accepted incorrectly (category II). However, as shown in Table 3, the Pilodyn and dynamic MOE predictors have approximately equal percentages of overall correct sorts for all the species combined, hardwoods only, and softwoods only populations.

If higher allowable unit stresses in compression are desired, there will be little or no change in the numbers of mine timbers falling in the accepted incorrectly category (II) but large increases in the rejected incorrectly category (IV).

**Allowable MOE (\(E_x\)) in compression parallel to the grain**

The basic design values for MOE are traditionally average values, with some adjustment possible for seasoning, density, and grade (2, 15). Reductions from the basic values are incorporated in intermediate and long column design formulas\(^4\).

Procedures have not been established for sorting timber populations into groups having acceptable average MOE values by measuring a related variable except that in conventional MSR practice, edge MOE is predicted, most often by flatwise bending.

Relationships developed in this study for the Pilodyn and dynamic MOE measurements versus static MOE measurements parallel to the grain were used to sort a mine timber population into groups having various levels of average MOE (\(E_x\)).

Figure 3 shows the plotted points of the dynamic MOE parallel to the grain static MOE relationship for all species of mine timbers combined. Successive groupings of mine timbers were screened or eliminated from the low end of the distribution of this population pool using sequentially higher levels of the prediction parameter. \(E_x\) was calculated for those timbers remaining in the population after each screening. For example, mine timbers remaining after sorting out those with a dynamic MOE less than 800,000 psi had an average static MOE of 1,100,000 psi (Fig. 3); at a dynamic MOE of 1,200,000 psi, the residual population had an average static MOE of 1,187,000 psi; at a dynamic MOE of 1,600,000 psi, the residual population had an average MOE of 1,300,000 psi, etc.

A curve was then plotted showing the relationship between arbitrary dynamic MOE sorting levels and the resulting average MOEs of residual populations. The dynamic MOEs required to sort out even allowable MOE values (1.1, 1.2, 1.3, and 1.4 million psi) were then determined from this curve.

Returning to Figure 3, the relative proportions of total mine timber population resulting from various go-no-go sorts could be determined. For example, a dynamic MOE reading of 1,260,000 psi would reject 71 timbers and accept 194 or 73 percent of the population with an average MOE of 1,200,000 psi.

Continuing with this procedure, we obtained the Pilodyn penetration and dynamic MOE measurements required to obtain allowable (average) MOE levels of

\[^{3}\]For softwoods the predicted strength must be 1.9 times the allowable stress \((F_c)\) to account for long time loading and a factor of safety; for hardwoods, 2.1 times higher (2).

\[^{4}\]If failure of a single prop is likely to lead to a catastrophic collapse of the support system, designers may consider not \(E_x\) but an \(E\) at a lower percentile.

---

Figure 3. Parallel-to-the-grain dynamic MOE-static MOE relationship—all species combined. An accept-reject sort based upon a minimum dynamic MOE of 800,000 psi is shown.
TABLE 4. - Levels of prediction parameter (X) required to achieve residual populations with various average MOE (Y) values; includes standard deviation (s), number (n), and percentage of the population accepted at each level.

<table>
<thead>
<tr>
<th>Species groupings</th>
<th>X*</th>
<th>Y (1,000 psi)</th>
<th>s</th>
<th>n</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>All species</td>
<td>48</td>
<td>1,100</td>
<td>413</td>
<td>311</td>
<td>95</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>1,200</td>
<td>385</td>
<td>220</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>1,300</td>
<td>380</td>
<td>114</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>1,400</td>
<td>375</td>
<td>35</td>
<td>11</td>
</tr>
<tr>
<td>Hardwoods only</td>
<td>44</td>
<td>1,100</td>
<td>450</td>
<td>192</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>32</td>
<td>1,200</td>
<td>420</td>
<td>182</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1,300</td>
<td>400</td>
<td>98</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>17</td>
<td>1,400</td>
<td>370</td>
<td>39</td>
<td>18</td>
</tr>
<tr>
<td>Softwoods only</td>
<td>60</td>
<td>1,100</td>
<td>305</td>
<td>116</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>1,200</td>
<td>275</td>
<td>65</td>
<td>56</td>
</tr>
</tbody>
</table>

DYNAMIC MOE PARALLEL TO GRAIN

| All species       | 800| 1,100        | 370| 243| 92      |
|                   | 1,260| 1,200       | 325| 194| 73      |
|                   | 1,600| 1,300       | 310| 154| 50      |
|                   | 1,980| 1,400       | 285| 75 | 28      |
| Hardwoods only    | 880| 1,100        | 425| 132| 87      |
|                   | 1,240| 1,200       | 390| 105| 70      |
|                   | 1,600| 1,300       | 355| 84 | 56      |
|                   | 1,940| 1,400       | 335| 66 | 44      |
| Softwoods only    | 400| 1,100        | 306| 113| 99      |
|                   | 1,300| 1,200       | 250| 89 | 78      |
|                   | 1,600| 1,300       | 210| 52 | 46      |
|                   | 1,800| 1,400       | 190| 22 | 19      |

*Pilodyn penetration in mm and dynamic MOE in 1,000 psi.

1.1, 1.2, 1.3, and 1.4 million psi for the various mine timber populations shown in Table 4. Also shown are standard deviations (s) for each sort, the number of timbers accepted at each allowable MOE (n), and the percentage of the total population this represents. Because of data limitations, curves to show the relationship between arbitrary Pilodyn sorting levels and average MOEs could not be plotted above 1.2 million psi for the softwoods group and these data are missing in Table 4.

Using dynamic MOE parallel to the grain to sort hardwoods or softwoods, grouped or separately, to obtain an allowable MOE of 1.2 million psi, we needed to reject no more than 30 percent of the timbers (Table 4). The accepted timbers had a COV (s/x) of 21 percent for the softwoods grouping, 32 percent for the hardwoods grouping, and 27 percent for all species combined. The Pilodyn as a prediction parameter generally had higher rejection rates and higher COVs at all levels of allowable MOE above 1.2 million psi. At an allowable MOE value of 1.1 million psi, the rejection rates and COVs obtained using the Pilodyn compared favorably with those obtained using dynamic MOE.

Conclusions

Pilodyn pin penetration measurements, using a 2.5-mm-diameter pin and an 18J force, correlated well with density, crushing strength, and MOE when mine props were segregated into a population of mixed hardwoods or identified as a hardwood species group (as suggested by the maple and oak results). For a population of mixed softwoods or for individual species, as suggested by southern pines and lodgepole pine, Pilodyn measurements gave only a fair estimate of crushing strength and poor estimates of density and MOE. With no botanical sorting, as for the all-species-combined grouping, there were good estimates of density and maximum crushing strength but only a fair estimate of MOE.

Dynamic MOE parallel to the grain gave good to excellent estimates of crushing strength and static MOE for all hardwoods combined and for the maples and the red and white oaks separately. Estimates of crushing strength and MOE of the softwoods, in combination or separately, were also good.

Both the Pilodyn and stress-wave instruments, as sorting parameters for crushing strength and MOE, were shown capable of stress-grading the sampled mix which was made up of 26 species and included decay levels ranging from sound to severely degraded.

Results of this mine timber study support the concept of species-independent "machine" stress rating (MSR) for unidentified "run-of-the-woods" timbers. More efficient utilization of the forest resource, tropical or temperate, is indeed a possibility.

Literature cited

12. JAMES, W.L., R.S. BOONE, and W.L. GALLIGAN. The feasibility of using the speed of sound in wood to monitor its drying progress in a kiln. Unpublished rept. USDA Forest Serv., Forest Prod. Lab., Madison, Wis.