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PREDICTING DURABILITY OF CLEAR FINISHES FOR WOOD FROM BASIC PROPERTIES

by H. E. Ashton

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SOMMAIRE

Le présent texte traite du rapport entre la composition, d'une part, et l'absorption d'eau, la perméabilité à la vapeur d'eau, la résistance à la traction et l'allongement, d'autre part, de feuils non pigmentés constitués d'une résine phénolique et d'un alkyde. On effectue les régressions simple et multiple des différentes propriétés modifiant la durabilité des matériaux exposés aux intempéries, après application sur des panneaux de cèdre rouge, afin de déterminer l'importance relative de ces propriétés eu égard à la durabilité. Il est démontré que l'on peut prédire, avec beaucoup de précision, la durabilité des résines phénoliques et des alkydes non pigmentés à partir des propriétés d'absorption d'eau et de perméabilité. La résistance à la traction des résines phénoliques et les propriétés mécaniques des alkydes revêtent une moins grande importance.

Predicting Durability of Clear Finishes For Wood from Basic Properties

H. E. Ashton
National Research Council of Canada*

The relations between composition and the water absorption, water vapor permeability, tensile strength and elongation of unpigmented phenolic and alkyd films are reviewed. Single and multiple regressions of the different properties on durability ratings of the materials exposed to natural weathering on red cedar panels are calculated to establish their relative importance in durability. It is shown that the durability of clear phenolics and alkyds can be predicted quite well from water absorption and permeability properties. Tensile strength of phenolics and mechanical properties of alkyds are of less importance.

INTRODUCTION

Although there is considerable demand for a clear finish for use on exterior wood, the performance of this type of coating has generally been so poor that it cannot be recommended for that purpose. Many materials have been suggested as suitable coatings. The evaluation techniques that led to the recommendations were evidently inadequate, though, because most materials have failed, some relatively quickly, when exposed either to accelerated weathering or on the test fence of the Division of Building Research, National Research Council of Canada.

One reason for this poor record is the ease with which exposed wood is attacked by two weather factors—solar radiation and water. Hence, a clear coating, that by itself is resistant to these elements, will not be a satisfactory finish for wood if it does not protect the substrate from them. A prime example is clear acrylics which are unaffected by ultraviolet light because they do not absorb it, but perform poorly as a clear finish on wood because the latter is rapidly degraded by the transmitted UV.

The need to conduct exterior exposure tests has also contributed to the problem of developing a satisfactory clear finish. When the Materials Section of DBR commenced work in this field, most materials failed after two summers. Now, however, some finishes resulting from this research have withstood nearly five years' exposure. Consequently, the time to establish whether a formulation is an improvement has more than doubled. While accelerated weathering can be used to eliminate unsatisfactory materials, those that appear to perform well still have to be exposed on the exterior because of occasional reversals between results of artificial and natural weathering, particularly with finishes containing ultraviolet absorbers.

Because of these factors, much of the development work in this area has been on an intuitive basis, rather than on an engineering approach using the basic properties of the materials to design a more suitable coating. The Materials Section undertook the study of the basic properties of clear finishes with the objective of determining which are important to the satisfactory performance of clear coatings for wood. Properties receiving the most attention were water absorption, water vapor permeability, tensile strength, and elongation at break. In this paper, the results of these basic property studies are summarized and their relation to durability considered.

EXPERIMENTAL

Materials

The clear finishes were prepared in the DBR laboratory so that their composition would be known and publishable. Clear alkyd resin solutions and phenolic varnishes, which have been studied the most, have been described in detail.[1] Results from earlier natural weathering tests have been documented and the method of coating the panels described.[2,3] The procedure for preparing free films for measuring the basic properties has been reported.[4]

Methods

Water absorption was measured using the quartz spring balance which has the sensitivity required to determine the small amounts of water absorbed by clear finishes. In addition to studying the effect of temperature, this technique permits a study of the effect of relative humidity on absorption, which is not possible with the simple, but imprecise, immersion method.

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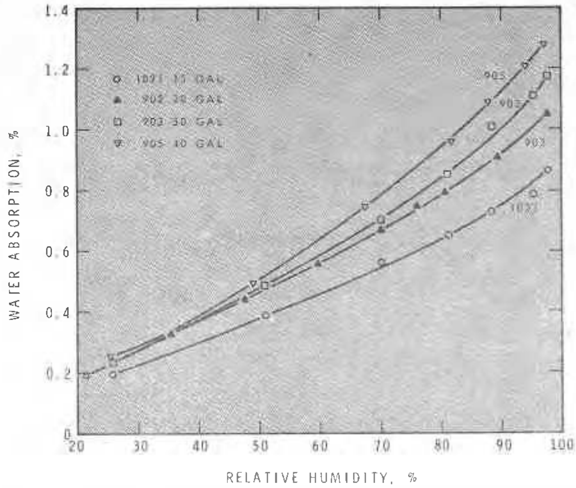

Figure 1—Relative humidity vs water absorption for linseed phenolics

Permeability was determined using the Payne cup with slight modifications.[1] The method followed is basically the dry cup procedure of ASTM E96, but at various levels of temperature or of RH, to study their individual effects on permeation.

Mechanical properties were measured on a tensile testing machine operating with a load of 600, 1200, or 2400 g for full scale deflection.[5] Tests were made on free films

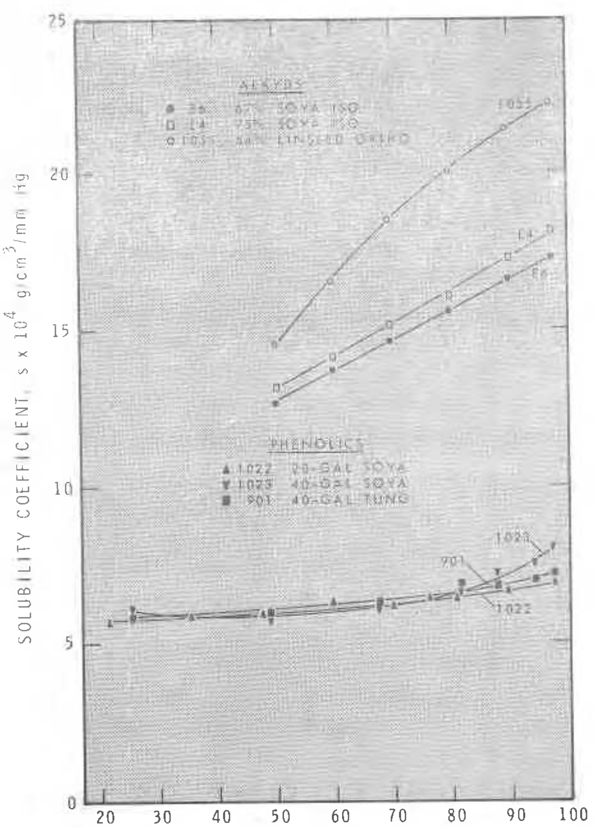

Figure 2—Comparison of solubility coefficients for alkyds and phenolics

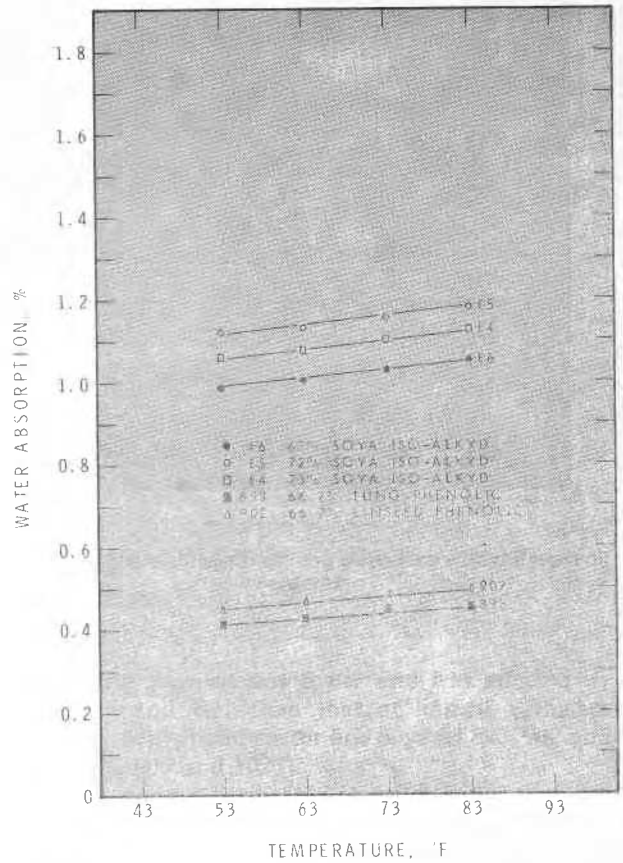

Figure 3—Temperature vs water absorption for phenolics and alkyds at 50% RH

subjected to various periods of natural or accelerated weathering to determine how tensile properties change.

Exterior exposure of coatings applied to western red cedar was conducted at Ottawa, Ontario. As noted,[3] the latitude of Ottawa is the same as that of Portland, Oregon, and Venice, Italy, so that, while latitude is not the only important factor, the exposure results are more widely applicable than sometimes assumed.

Artificial weathering of free films took place in a twin carbon-arc Weather-Ometer® operating on the cycle of 12 hr light without water and 12 hr without light but with high humidity to avoid damage by the usual water spray.

BASIC PROPERTY RESULTS

Absorption

Phenolic varnishes with higher oil contents absorb more water than those with low oil contents and the differences are greater at higher relative humidities (*Figure* 1). Tung oil phenolics are somewhat less hydrophilic than their counterparts based on other oils, although at lower oil contents the differences are not significant. Absorption of water by phenolics shows a slight linear increase with increasing temperature. This

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Weather-Ometer is a registered trademark of Atlas Electric Devices Co.

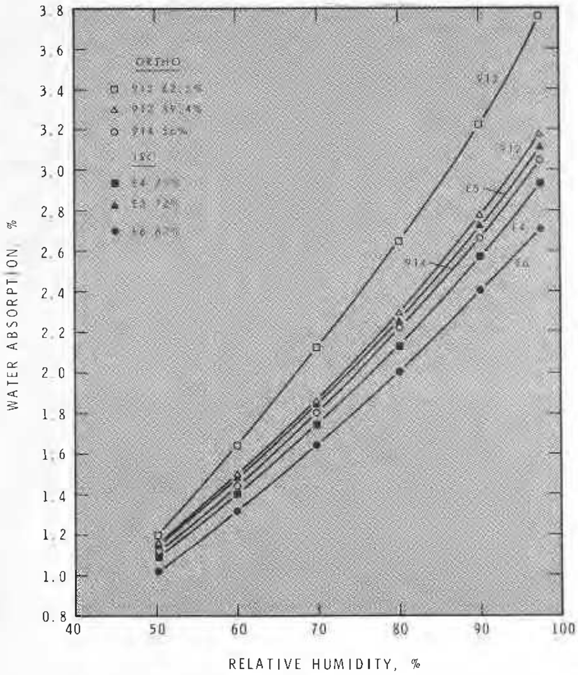

Figure 4—Relative humidity vs water absorption for soya alkyds

indicates that the effect of temperature is proportional to the activation of the groups responsible for absorption.

At 50% RH, unpigmented alkyds absorb twice as much water as phenolics, and above 90% RH the ratio is almost 3:1. The greater effect of moisture on alkyds is shown in *Figure* 2, where the solubility coefficients are compared. Absorption by alkyds is affected more by temperature than is that of phenolics, as illustrated in *Figure* 3. The greater hydrophilic characteristics in humid or warm environments are evidence that all the alkyd ingredients are not completely reacted and that some polar groups are retained. The difference in the slopes of water absorption vs temperature, about 1:1.7, can be used as an approximate measure of the activity with respect to water of the polar groups in the phenolics and alkyds studied here.

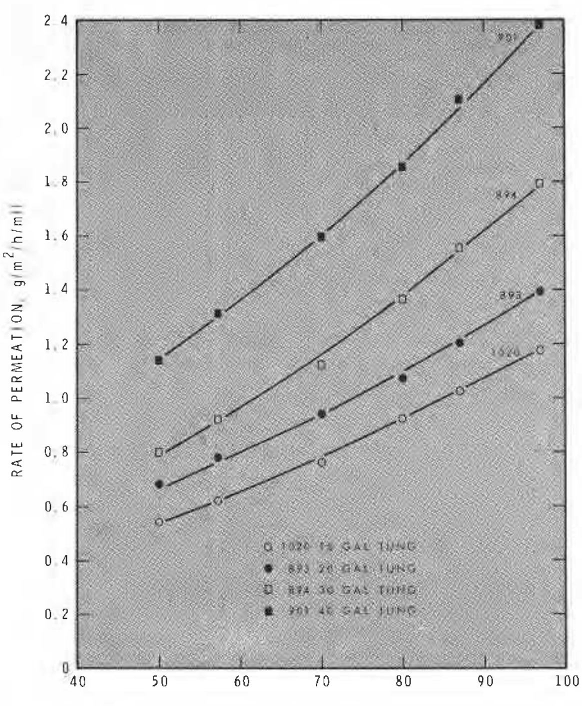

Figure 5—Relative humidity vs permeation rate through phenolics with different oil contents

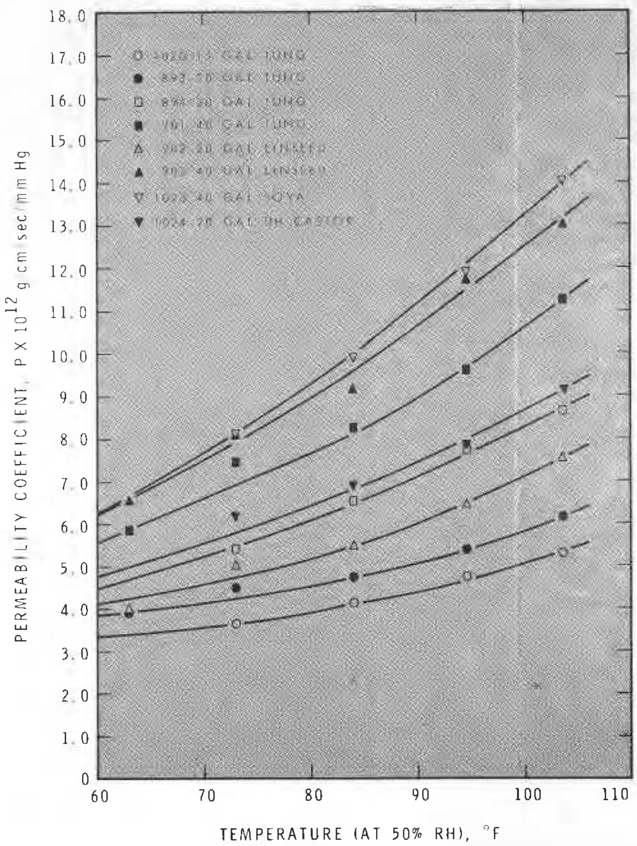

Figure 6—Effect of temperature on permeability coefficient of phenolic varnishes

Water absorption decreases with decreasing oil content with some, but not all, the ortho and iso alkyds. For example, the three longest soya ortho alkyds, shown in *Figure* 4, are in this order, but the two shortest ones behave similarly to the second longest alkyd. The results indicate that iso alkyds are less hydrophilic than ortho alkyds, although they contain considerably more oil. Because a change in oil content has little effect on polar group concentration, oil content does not appear to be the major factor that controls water absorption by alkyds. Other factors of importance, besides the phthalic isomer, are polyol content and extent of the alkyd reaction.

Permeability

With phenolic varnishes, oil content affects water permeation more than absorption (*Figure* 5). Changes in permeation and permeability coefficient caused by increasing RH (*Figure* 5) and temperature (*Figure* 6) are smaller for varnishes containing less oil. The permea-

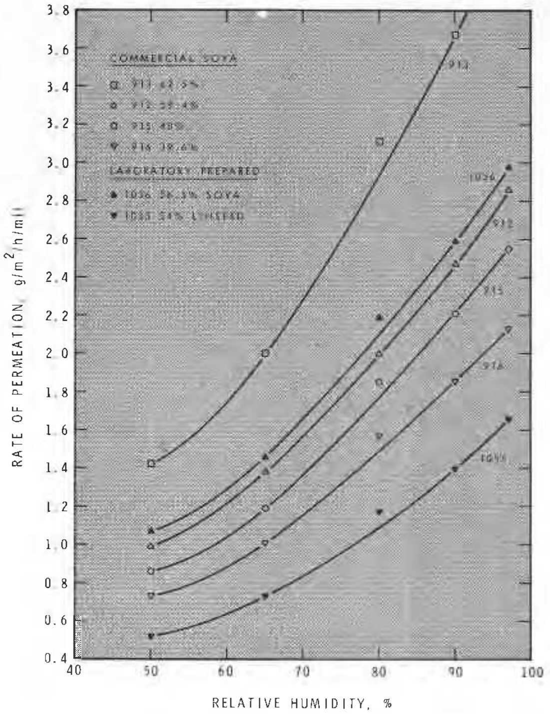

Figure 7—Relative humidity vs water permeation for ortho alkyds

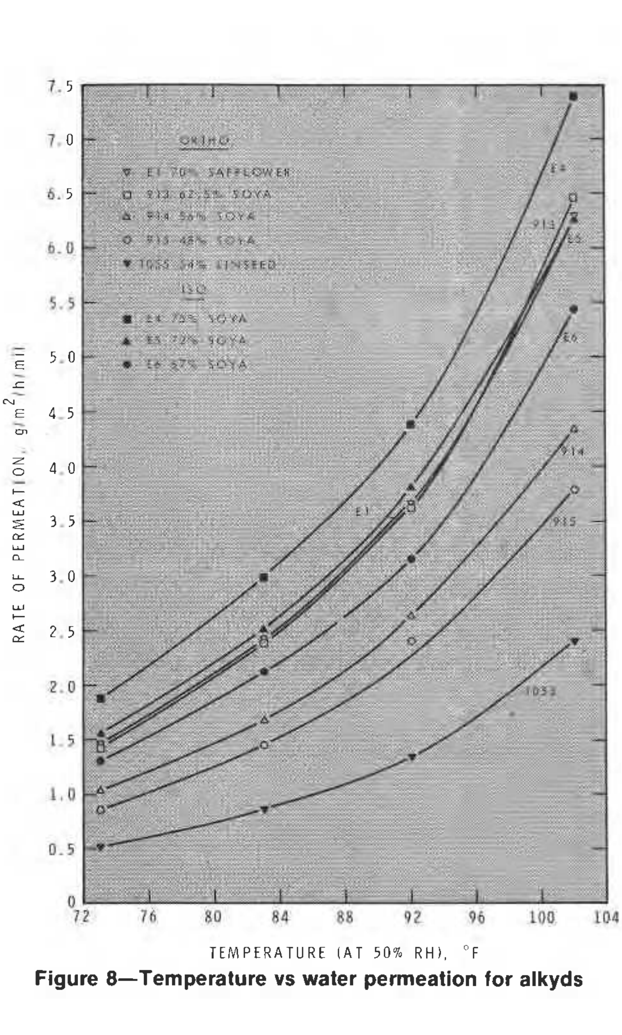

Figure 8—Temperature vs water permeation for alkyds

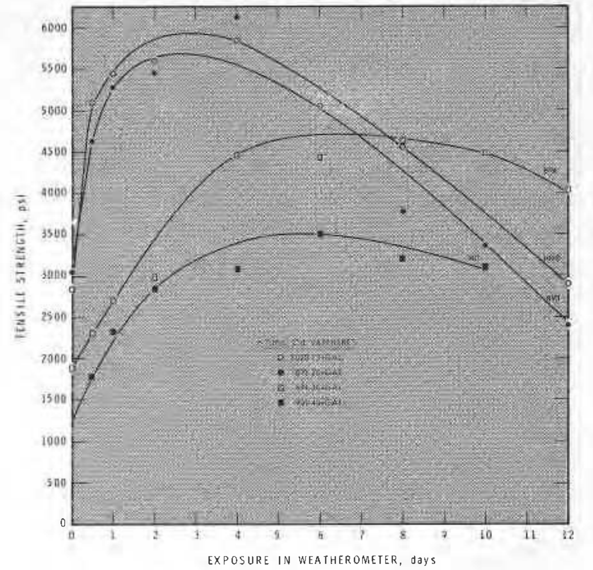

Figure 9—Tensile strength of tung phenolics with different oil contents

bility of tung varnishes is lower and less affected by temperature and RH than that of linseed varnishes followed by dehydrated castor and soya (cf 893, 902 and 1024 vs. 901, 905 and 1023).

Alkyds are more permeable to water vapor than are phenolics. In contrast to absorption, decreasing oil content leads to decreasing permeation by alkyds (*Figure* 7). The effect of oil type is also evident in this figure where the linseed alkyd is much less permeable than soya alkyds of equal or lower oil content.

Permeation rates through alkyds are more affected by temperature than are those of phenolics. Increasing permeation with a rise in temperature is more marked with ortho than iso alkyds and with soya than linseed and safflower alkyds (*Figure* 8).

The differences in permeability and in the effect of temperature and RH on permeability between phenolics and alkyds, and between different coatings in the same class, can be explained on the basis of composition. In a highly crosslinked material, the movement of segmental chains and the formation of spacings are restricted, thus reducing permeation. Phenolic resins have a more highly condensed structure, which is reflected in lower permeability. The oil portion of coatings has a much more open structure, resulting in lower resistance to water transmission. Tung oil, because of its high degree of conjugated unsaturation, forms more crosslinks with resins and itself than do other oils, so that tung-based varnishes are not only less permeable and absorb less water, but also are stronger mechanically than varnishes made with other oils.

Mechanical Properties

Phenolic varnish films exposed to accelerated weathering increase rapidly in tensile strength while flexibility decreases abruptly. With regard to oil content, varnishes containing more oil have lower tensile strengths that peak a few days later than short oil varnishes (*Figure* 9). As with

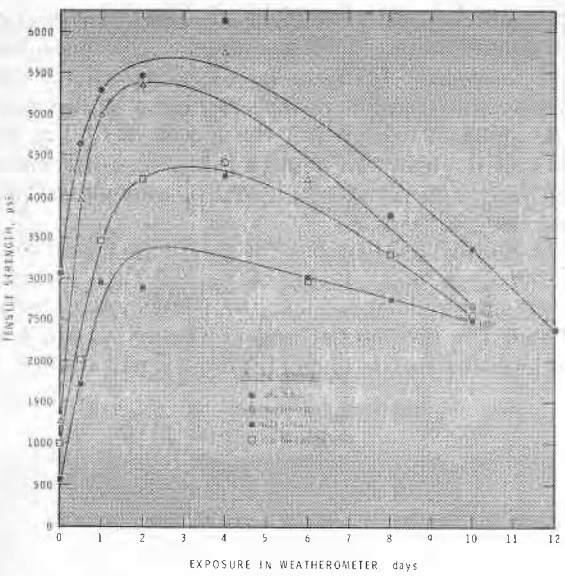

Figure 10—Tensile strength of phenolics with different oil types

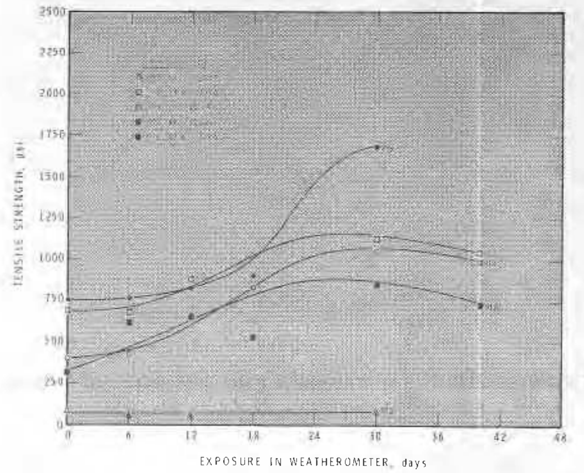

Figure 12—Tensile strength of alkyds with different oil contents

permeability, the strength of linseed varnishes approaches that of tung varnishes, with dehydrated castor and soya being somewhat lower (*Figure* 10). Regardless of oil type, all 20-gal varnishes lose flexibility after one day of accelerated weathering. Only the 40-gal soya and DH castor varnishes retain flexibility for more than eight days.

Free films of phenolic varnishes exposed to natural weathering behave similarly to those in artificial weathering, although the peak in tensile strength is lower and the changes more gradual in natural weathering. The elongation results illustrate why high oil content is not related to durability of phenolics. The 20-gal varnishes made with all four oils have the same low level of flexibility after 15 days' exposure. Those containing 80% oil, however, also have low elongation after 45 days' weathering (*Figure* 11). Because all varnishes, whether short or long oil, become relatively inflexible within less than two months of weathering, high oil content cannot be an important factor in durability.

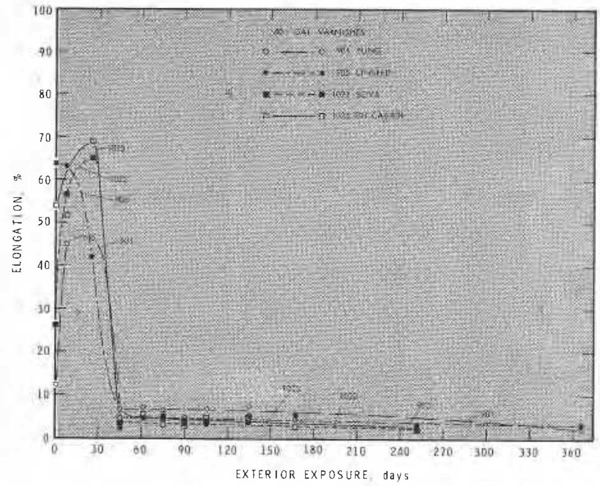

Figure 11—Flexibility of phenolics with different oil types

Compared with phenolics, alkyds have much lower tensile strengths that, except for long ortho and very long iso resins, increase gradually during accelerated weathering. As with absorption, tensile strength decreases with increasing oil content with some, but not all, of the alkyds (*Figure* 12). Iso alkyds tend to be somewhat stronger than ortho alkyds of similar or even lower oil content.

The elongation results do not reflect the usual assumption that high oil content is needed for flexibility. The

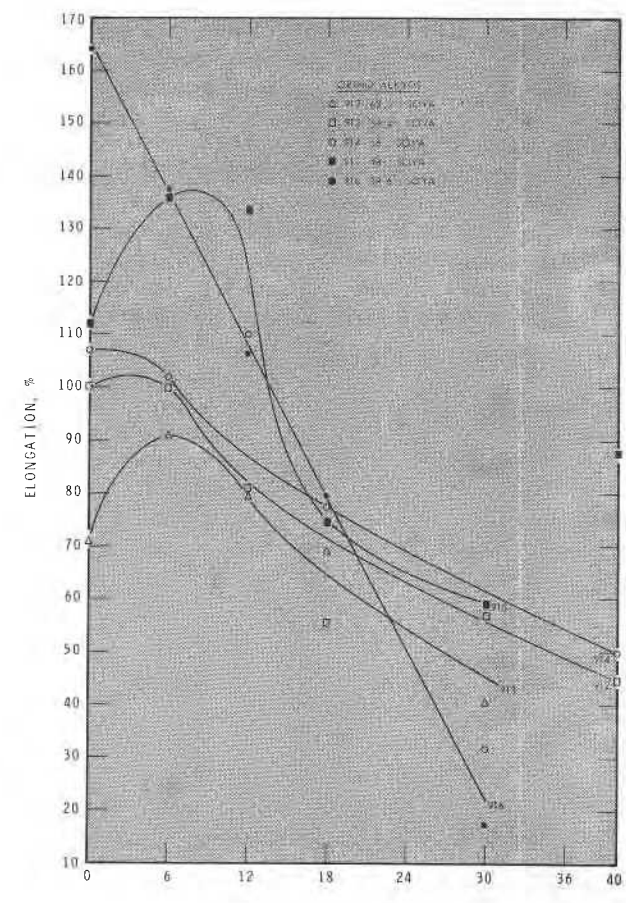

Figure 13—Flexibility of alkyds with different oil contents

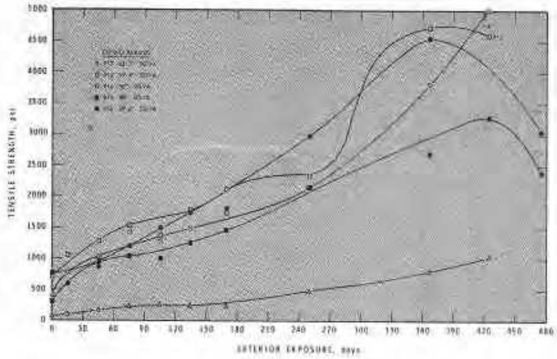

Figure 14—Tensile strength of alkyds with different oil contents

short oil alkyd with the highest tensile strength also has the greatest initial elongation (*Figure* 13). This, however, eventually drops to the lowest in keeping with the marked increase in strength. In the ortho soya group, the one containing 62.5% oil has the lowest flexibility during most of the test, even though it has very little strength. The resin with the second lowest oil content has the second highest flexibility.

In contrast to phenolics, the maximum tensile strength of alkyds is much higher in natural than in artificial weathering and is not reached until after a year's exposure (*Figure* 14). Most of the longer oil resins are still increasing in strength at the end of the test when flexibility corre-

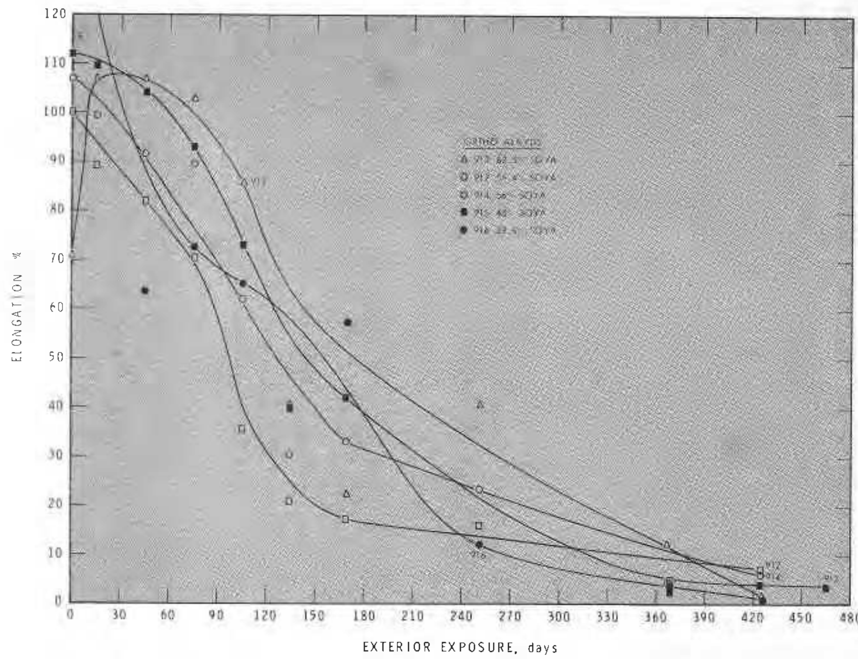

Figure 15—Flexibility of alkyds with different oil contents

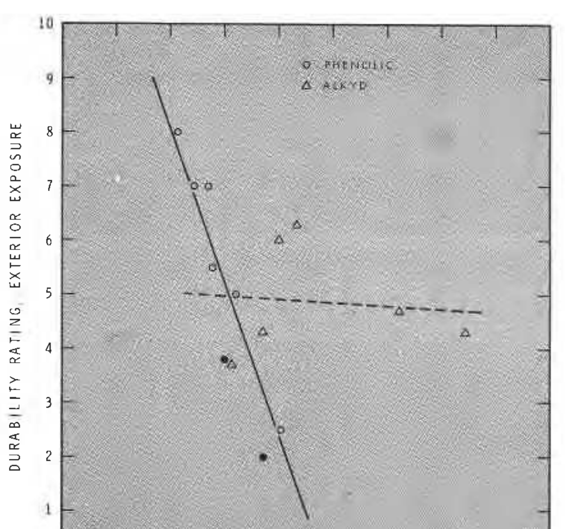

Figure 16—Permeability vs durability

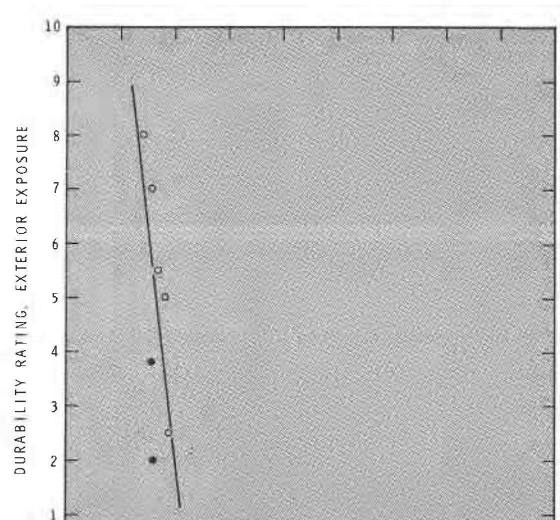

Figure 17—Absorption vs durability of phenolics

Table 1—Correlations Between Phenolic Varnish Properties and Durability Ratings

Property or Properties	Regression Equation Factors: Permeability	Absorption	Tensile Strength	Constant	Correlation Coefficient, r	F	Regression Slope Actual vs Predicted Durability
Permeability	−5.64	—	—	13.7	−0.88	20.3	0.77
Absorption	—	−17.2	—	19.4	−0.58	3.0	0.33
Tensile strength	—	—	0.22	− 4.61	0.89	22.3	0.79
Permeability and tensile strength	−1.99	—	0.15	1.72	0.89	23.2	0.79
Absorption and tensile strength	—	5.6	0.26	−10.8	0.90	24.5	0.86
Permeability and absorption	−8.06	13.7	—	6.11	0.92	31.3	0.84
Permeability, absorption, and tensile strength	−6.36	12.5	0.06	1.87	0.92	32.2	0.84

Table 2—Correlations Between Alkyd Properties and Durability Ratings

Property or Properties	Regression Equation Factors: Permeability	Absorption	Tensile Property, PTS, Elong., or Tensile Parameter	Constant	Correlation Coefficient, r	F	Regression Slope: Actual vs. Predicted Durability
Permeability	0.046	—	—	4.84	0.04	0.01	—
Absorption	—	−2.69	—	11.35	−0.39	0.54	—
Elongation, 30 days accel. weath.	—	—	0.047	2.60	0.70	3.75	0.48
Absorption and elongation	—	−1.24	0.047	5.67	0.75	3.94	0.57
Tensile strength and elongation	—	—	0.048 PTS 0.0565 El	1.74	0.75	5.2	0.56
Permeability and elongation	−0.189	—	0.050	2.92	0.71	4.1	0.51
Permeability and AW tensile parameter	1.606	—	0.0057 TP	−1.04	0.91	20.4	0.86
Permeability and absorption	2.66	−10.3	—	23.6	0.939	22.5	0.88
Permeability, absorption and elongation	2.845	−11.0	−0.006	2.52	0.94	22.7	0.88
Permeability, absorption and peak tensile strength	3.18	−10.3	0.055	22.0	0.946	25.7	0.90
Permeability, absorption and tensile parameter	2.08	−0.028	0.006	−1.92	0.97	48.4	0.94

Table 3—Tensile Parameter Derived from Tensile Strength and Elongation

NRP Formula No.	Natural Weathering: Peak Tensile Strength psi ÷100	Elongation Estimated at 180 days, %	Tensile Parameter	Accelerated Weathering: Peak Tensile Strength psi ÷100	Elongation Estimated at 30 days, %	Tensile Parameter
912	47	17	800	11.2	56	627
913	10.5	50	525	0.8	45	36
914	50	30	1500	10.5	62	651
915	33	40	1320	8.5	59	501.5
916	45.5	40	1820	17.5	22	385
E3	13	55	715	0.7	55	38.5

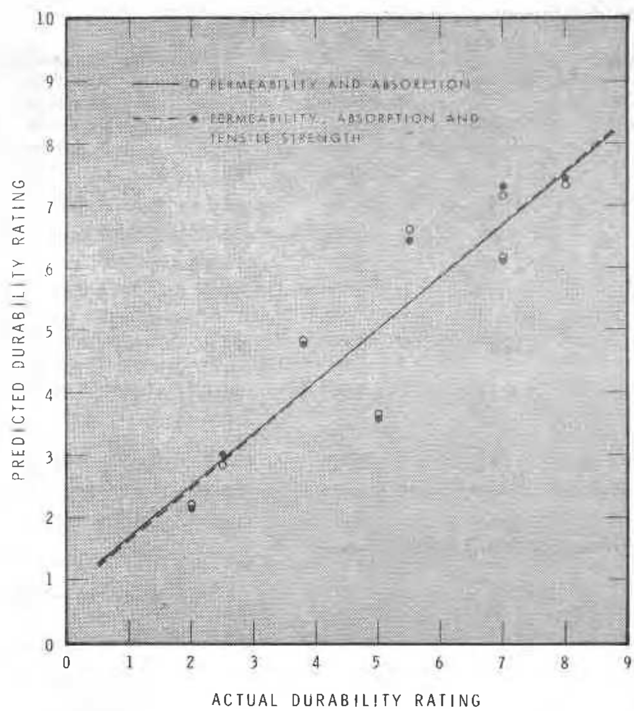

Figure 18—Phenolic durability predicted from basic properties

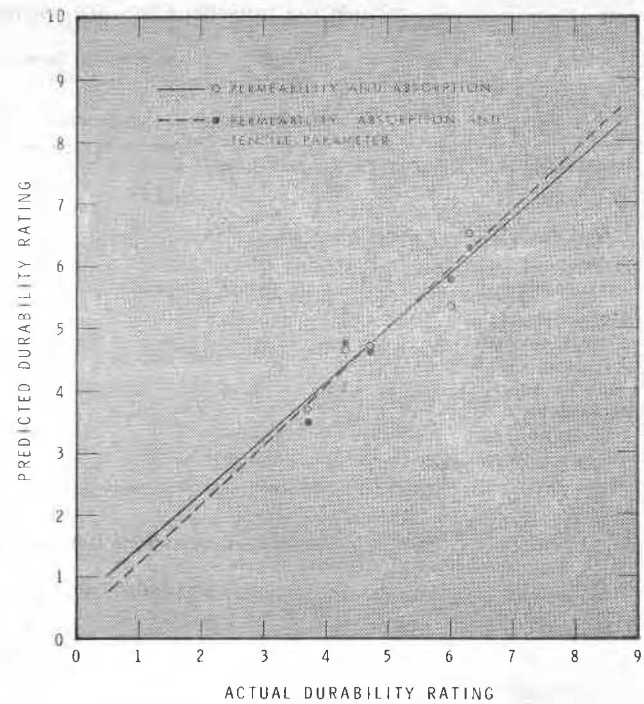

Figure 19—Alkyd durability predicted from basic properties

spondingly decreases. This figure also shows that shorter alkyds after one year exhibit a decrease in strength not evident in the brief artificial test. The long oil iso alkyds (not shown) are again comparable in strength to the medium ortho resins.

In accord with the higher tensile strengths, the elongation results from the three intermediate soya ortho alkyds are lower in natural weathering (*Figure* 15). The longest resin now has the highest flexibility in the ortho group but the second longest has the lowest flexibility for the first eight months. As in artificial weathering, the shortest iso alkyd, E6, has the best elongation throughout the test, followed by that with the second lowest oil content. The good flexibility together with the higher strength of the long oil iso alkyds suggest that the oil reacts more during resin preparation to become a part of the molecule.

RELATION OF BASIC PROPERTIES TO PERFORMANCE ON EXTERIOR WOOD

Not all of the finishes studied have been exposed on exterior cedar panels because some were added as a result of the exposure tests. Consequently, it is not possible in all cases to relate basic properties to test fence performance. To study the relation between durability and water absorption or water vapor permeability, the values obtained at 80% RH were selected because differences between coatings are more evident at high humidities and because this RH corresponds to the stage where surfaces can become wet.[6] With tensile properties, it was necessary to estimate values from the curves rather than use the actual value at a given time because the latter may not be representative of the general trend, owing to the large scatter in tensile results. Examples of divergent elongation values are 915 at 40 days and 914 at 30 days (*Figure* 13).

In the exposure studies, the phenolic varnishes containing 67 and 75% tung oil and 67% linseed oil were most durable.[2] Their good durability appears to be related, at least in part, to their low water vapor permeability, low water absorption and high peak tensile strength. To establish on a quantitative basis which of the properties are important to durability, correlation coefficients were calculated using results from all the phenolics that had been exposed on panels.

The correlation coefficient, r, can vary from +1, when there is a positive, perfect functional relationship between two variables, to −1 when the perfect relationship is negative. When $r = 0$ there is no relation, while intermediate values indicate that the variables are correlated, i.e., although the relation is not strictly functional, there is an association between the variables. The closer that r is to +1 or −1, the more nearly the correlation approaches a strictly functional relationship. A high correlation coefficient, however, may be partly the result of low scatter of points about the regression line. Accurate prediction of the values of one variable from those of the other requires that the slope of the regression line also approach 1, when both variables are in the same units.

Calculation of the regression between permeability and durability of phenolics showed that the two properties are linearly related, even though two of the values marked in *Figure* 16 with solid circles are only durability ratings estimated from similar varnishes exposed in the first series. The water absorption-durability regression line for phenolics shown in *Figure* 17 is almost parallel to the durability axis because of the narrow range in absorption results. The correlation coefficients for permeability, absorption, and tensile strength with respect to durability are −0.88, −0.58, and +0.89, respectively, showing that low permeability and high tensile strength correlate well with durability. When durability ratings were calculated using the regression equations, however, the slopes for both permeability and tensile strength were below 0.8. Thus, neither of the individual properties predicts durability very well in spite of their high correlation coefficients.

If the two properties, permeability and tensile strength, are jointly correlated vs. durability, the values are changed only slightly, as shown in *Table* 1. Combining absorption with either of the preceding properties, however, increases the slope to about 0.84 and the multiple correlation coefficient for permeability and absorption is 0.92. The combination of all three properties has a negligible increase on the values of r and the slope. Thus, the durability of the phenolic varnishes used in this study can be predicted quite well from the two basic properties of water absorption and permeability (*Figure* 18) using the equation:

$$\text{Durability} = -8.06\ (\text{Permeability}) + 13.68\ (\text{Absorption}) + 6.11$$

For an exposure period different than that used here, the factors in the multiple regression equation would, of course, change.

With the alkyds, it is more difficult to relate basic properties to durability as only a limited number had been exposed on the test fence. Because durability of alkyds reaches a maximum at intermediate oil contents, a high correlation for a linear regression with a single property that changes linearly with oil content, such as permeability, would not be expected (*Figure* 16). There is a stronger relation between absorption which reaches a minimum at oil contents where durability peaks and durability, but the correlation coefficient is still only −0.4 (*Table* 2). As discussed earlier, both high tensile strength and good elongation retention in alkyds seem to be related to durability, but a multiple correlation of the two with durability only increased r to 0.75 compared with 0.70 for elongation alone.

Because these mechanical properties are generally inversely related, an attempt was made to combine them into a single factor in which one would not tend to cancel the other. This was done by multiplying the peak tensile strength reached in weathering by the elongation after a given exposure—30 days for accelerated and 180 days for natural weathering. The resulting tensile parameter, shown in *Table* 3, was used to calculate multiple regressions with other alkyd properties. In most cases, there was little improvement except where it was used with permeability.

The multiple regression of permeability and absorption against durability had at first been ignored because the individual correlation coefficients were so low. When the regression was calculated for this combination, however, it had the highest coefficient and slope for two factors. Addition of either elongation or tensile strength caused merely minor changes in both values and only the multiple regression of the tensile parameter with permeability and absorption increased r and the slope (*Figure* 19). Consequently, the water vapor permeability and water absorption properties of clear alkyds can be used to predict their durability by the equation:

$$\text{Durability} = 2.66\ (\text{Permeability}) - 10.3\ (\text{Absorption}) + 23.6$$

Because of the marked differences between the properties of phenolics and alkyds, the highest r for any combination of the properties of the two groups was only 0.71 with a slope of 0.51.

CONCLUSIONS

It has been shown that durability of phenolic varnishes exposed naturally for two years is related to their water absorption, water vapor permeability and, to a smaller extent, tensile strength, while it is unrelated to flexibility. For alkyds, the same two properties are related to durability with a smaller contribution from a tensile parameter which combines elongation after 30 days with the peak tensile strength in accelerated weathering.

The formulas relating the basic properties of these two types of materials to performance do not, unfortunately, take into account the effect of ultraviolet light on the durability of wood coated with a clear finish. Nevertheless, the results of the basic property studies should be helpful in designing a more satisfactory clear finish. For example, the isophthalic alkyd resins with the best mechanical and water absorption properties certainly appear worthy of further study.

ACKNOWLEDGMENTS

The basic property results given in this paper were obtained under the direction of M. Yaseen, now of the Regional Research Laboratory, Hyderabad, India, when he was a post-doctoral fellow working with the author at the National Research Council of Canada. The preparation of the varnishes and the films by G.A. O'Doherty, L.R. Dubois, and R.C. Seeley is acknowledged with thanks. Mr. Seeley also measured the mechanical properties of the films.

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