MATHEMATICAL MODELS FOR PREDICTING KILN-DRYING TIME AND MODIFYING KILN SCHEDULES FOR SOME PHILIPPINE HARDWOOD SPECIES

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ABSTRACT

Three models based on Bramhall's drying-effort method for calculating kiln-schedule modifications were developed to determine the reliability of the method to the kiln drying of some Philippine hardwood lumber species. The general form of the models is based on Bramhall's vapor-pressure gradient concept of bound-water diffusion, and is basically dependent on empirically determined relationships between the resistance-to-drying (R) and the average charge moisture content ($\overline{M}$). Functional R-$\overline{M}$ relations were established for three species-thickness combinations of Philippine hardwoods using simple linear regression techniques. In all cases, an exponential relationship of the form $R = A \exp(-b\overline{M})$ was observed. Chi-square tests on several comparisons between predicted and observed drying times showed that the models are sufficiently valid and accurate at 5% level of significance. The models are best fitted to the species-thickness combinations tested but it appears that they are also applicable to the kiln drying of mixed kiln charges involving other lumber species of comparable wood density.

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KEY WORDS: Drying-effort method. Resistance-to-drying. Kiln-drying time. Kiln charge. Kiln runs. Kiln schedule. Species-thickness combination. Mix-drying.

INTRODUCTION

Kiln drying of lumber is an "energy-intensive" process. It is estimated that close to 190 x 10^{10} B.t.u. of heat energy is being generated and utilized each year by the Philippine lumber industry for this purpose alone (Bello, 1980). Undoubtedly, the production of such quantity of heat by burning either oil or wood residue fuel requires tremendous amount of investment. Due to the spiralling cost of fuel oil in both local and foreign markets, and to the increasing cost of utilizing wood residues for heat generation, inexpensive means of accelerating the kiln-drying process need to be explored in order to reduce kiln-drying time.

About 10 years ago, Bramhall (1976) developed a simple and inexpensive method of reducing fuel consumption in kiln drying through the manipulation of kiln schedules. His so-called drying-effort method for predicting kiln-drying time and modifying kiln schedules appears valid and feasible in reducing kiln-drying time by 15-25% (Cheng and Arganbright, 1981). In Canada, some kiln-drying specialists involved in the commercial drying of softwood lumber have already tried the method with considerable degree of success (Bramhall, personal communication). To the authors' knowledge, however, the method has not been extensively tested on hardwood lumber species. It is possible that the more unwieldy drying characteristics of hardwoods compared to softwoods will render the method invalid for this particular group of species.

This study was conducted to determine the applicability of Bramhall's method to the kiln drying of some Philippine hardwood lumber species, and to develop a reliable data base for calculating kiln schedule modifications.

MATERIALS AND METHODS

Model Development

Kiln-drying data for three species-thickness combinations of Philippine hardwoods, namely: 2-inch mayapis-bagtikan, 1-inch tangile-red lauan, and 1-inch mayapis-bagtikan, were collected from various sources. The data were summarized to include the initial and final average charge moisture contents, the momentary charge moisture contents at predetermined time intervals, the dry-and wet-bulb kiln temperatures from start to final period of drying, and the kiln-setting durations.

Resistance-to-drying values (R) were computed using Bramhall's (1976) equation as follows:

$$R = \frac{[(h_o)_{DB} - (h_o)_{WB}]\, \Delta t}{\Delta \overline{M}}$$

where: $(h_o)_{DB}$ and $(h_o)_{WB}$ = saturated vapor pressures of water at the dry- and wet- bulb temperatures, expressed in millibars (mb), respectively and calculated using Antoine's equation (Bramhall, 1979).

$\Delta\overline{M}$ = change in momentary charge moisture content (MC) for the time interval, Δt.

Computed R values were plotted against corresponding mean MCs at each time interval (Δt) using a semi-log paper. Since the plots were essentially linear, a series of simple linear regression analysis were performed using $\ln(R) = \alpha + \beta\overline{M} + \varepsilon$, as the hypothetical model, where α is the intercept of the true regression model, β is the regression coefficient associated with the average charge moisture content ($\overline{M}$) and ϵ is a random error term. Established R-$\overline{M}$ relations were then transformed into $\ln(R) = a + b\overline{M}$ and $R = A\exp(b\overline{M})$, where a and b are estimates of the parameters α and β, respectively, and $A = \exp(a)$. The latter equation satisfies the empirical requirement of Bramhall's drying-effort equation which is written as:

$$-\int_{\overline{M}_1}^{\overline{M}_2} [R = f(\overline{M})]\, d\overline{M} = \sum_{i=1}^{n} (\Delta ho)_i\, t_i \quad (1)$$

where:

$\overline{M}_1$ and $\overline{M}_2$ = initial and final average charge moisture contents, respectively

$(\Delta h_o)_i$ = saturated vapor pressure differential corresponding to the dry-and wet-bulb temperatures of the i-th kiln setting

n = number of steps in the schedule

t_i = i-th kiln-setting duration.

The empirical constants a and b were adjusted by trial-and-error method until the equality sign in equation (1) was satisfied. This method was repeated for each of the kiln schedules used, and the mean values for a and b were incorporated in the final models.

Model Validation

To check the validity of the models, several comparisons between predicted and actual drying times were performed using the data from 18 runs of mixed Philippine Mahogany[1] (predominantly maya-

[1]Philippine Mahogany is a trade name for seven commercial species of Philippine hardwoods, namely: mayapis [*Shorea palosapis* (Blco.)], red lauan (*S. negrosensis*), white lauan (*S. contorta* Vidal), almon (*S. almon* Foxw.), tangile [*S. polysperma* (Blco.) Merr.], tiaong (*S. agsaboensis* Stern), and bagtikan [*Parashorea malaanonang* (Blco.) Merr.]

pis and bagtikan), which were collected from a commercial kiln-drying plant in Valenzuela, Bulacan. The data were used in addition to the kiln runs already used in developing the models.

Predicted kiln-drying times were calculated by integrating the left side of equation (1) for the moisture reduction ($\overline{M}_1$ - $\overline{M}_2$) and adjusting the last kiln-setting duration (t_n) so that the total sum of the products of Δh_0 and t becomes equal with that of the left integral. The difference between the actual (last) setting duration and the adjusted t_n was considered as the drying-time prediction error. Chi-square tests of accuracy as described by Freese (1960) were performed to determine whether or not the models met the desired accuracy level.

To predict the drying times of mixed kiln charges coming from a definite kiln source, a correction factor, referred to by Bramhall (1976) as "kiln factor", was computed for each model by taking the average ratio (over all kiln runs) of the actual millibar-hour (mb-hr) units expended by the kiln schedule and the mb-hr units specified by the model. The kiln factor accounts for errors due to peculiarities of individual kilns, variations in composition and properties among kiln charges, and errors due to the mix-drying of two or more lumber species within a single charge.

RESULTS AND DISCUSSION

Model for 2-Inch Mayapis-Bagtikan Lumber

The empirical basis for the model is graphed in Figure 1. Two important findings are reflected in the figure as follows:

(1) A linear relationship exists between the natural logarithm of R and the average charge moisture content, $\overline{M}$. This can be expressed mathematically as $\ln(R) = a + b\overline{M}$, or conversely as $R = A \exp(b\overline{M})$ where $A = \exp(a)$. Here, an exponential dependency of R on $\overline{M}$ is evident. In the study of Bramhall (1976) on three softwood lumber species, the same R-$\overline{M}$ relation for Western white spruce and Alpine fir was also noted.

(2) The plot of ln(R) versus $\overline{M}$ for mayapis (Runs 1 to 3) combines well with that for bagtikan (Run 4). This may be construed to mean that the two species have approximately equal rates of drying, and that a single R-$\overline{M}$ relation could represent both species reasonably well. Incidentally, this observation could provide a scientific basis for the recommended and commercial practice of mix-drying the two species within a single charge. Other species of comparable density may exhibit the same R-$\overline{M}$ relation as that for mayapis and bagtikan (Bramhall, personal communication).

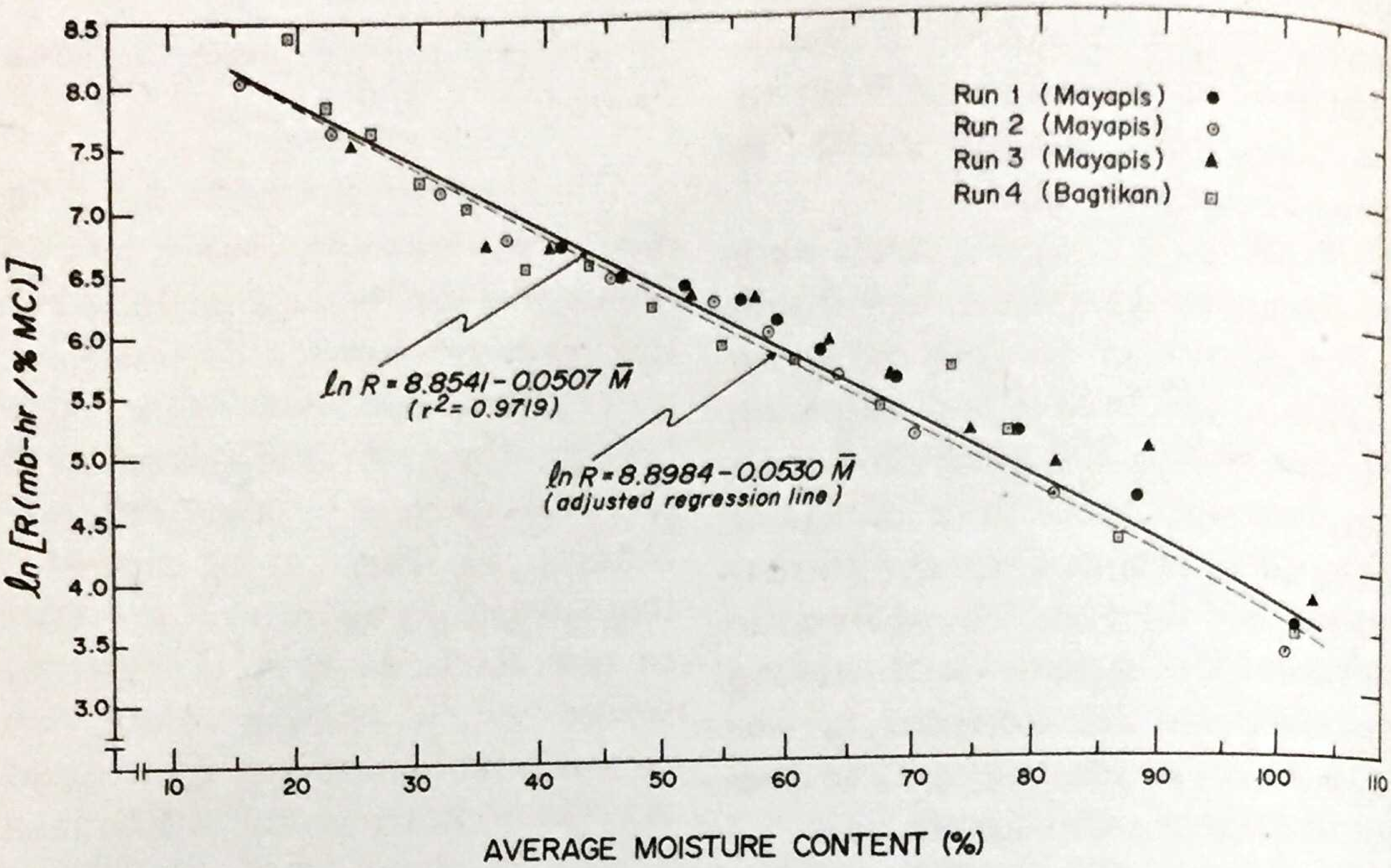

Figure 1. Natural logarithm of the resistance-to-drying (R) as a function of the average charge moisture content ($\overline{M}$) for four runs of 2-inch mayapis-bagtikan lumber.

Combined regression analysis for Runs 1 to 4 yields the following mathematical model for 2-inch mayapis-bagtikan:

$$\int_{\overline{M}_1}^{\overline{M}_2} 7320 \exp(-0.053\overline{M})\, d\overline{M} = \sum_{i=1}^{n} (\Delta h_o)_i t_i$$

which can be integrated as

$$138113.2 \exp(-0.053\overline{M})\Big]_{\overline{M}_1}^{\overline{M}_2} = \sum_{i=1}^{n} (\Delta h_o)_i t_i \quad (2)$$

The above model suggests that if a charge of lumber is dried from an initial average moisture content ($\overline{M}_1$) to another moisture content ($\overline{M}_2$), the sum of the products of vapor-pressure differential and time is constant. This implies that different combinations of Δh_o and t, hence different kiln schedules, could be devised to effect the same amount of drying or moisture change. Using this principle, it is possible to shorten kiln-drying time by increasing the vapor-pressure differential (Δh_o) or by shifting to higher kiln temperatures.

The validity of equation (2) was checked by comparing the predicted and the observed drying times in Runs 1 to 4. The summary of calculations is shown in Table 1. Except for Run 1 (error = 18.7 hrs or 8.2%), the other three runs show little discrepancy between predicted and actual drying times. Result of chi-square test (Table 1) shows that the observed prediction errors are acceptable. In general, the observed errors may be attributed to: (a) errors in estimating the initial and final charge moisture contents, (b) errors caused by variations in the composition and properties of dif-

Table 1. Comparison of predicted and actual drying times for 2-inch mayapis-bagtikan lumber (Runs 1 to 4).[1]

Parameter	Run Number			
	1	2	3	4
Initial MC (%)	110.0	111.0	123.0	110.3
Final MC (%)	19.0	14.0	16.0	18.7
$\int Rd\overline{M}$ of final MC (mb-hr)	50456	65766	59151	51264
$\int Rd\overline{M}$ of initial MC (mb-hr)	406	385	204	399
Net $Rd\overline{M}$ (mb-hr)	50050	65381	58947	50865
Actual $\Sigma(\Delta h_o)_i\, t_i$ (mb-hr)	41721	62813	57737	53799
Actual drying time (hr)	288	350	385	360
Predicted drying time (hr)	246.7	355.8	388.3	351.7
Error (hr)	+18.7	+5.8	+3.3	-8.3
Error (%)[2]	+8.2	+1.7	+0.9	-2.3

[1]Chi-square test result: $\chi^2_c = 7.91 < \chi^2_{t\,(0.05,\,4)} = 9.48$ based on a tolerable prediction error (E) of 15 hours.

[2]Based on actual drying time.

ferent kiln charges of the same species-thickness combination, and (c) errors inherent in the model itself as a result of the oversimplification of the mathematics involved.

As an additional check, the model was used to predict the drying times of 10 commercial runs of mixed charges predominated by mayapis and bagtikan (Runs 5 to 14). A comparison between predicted and actual drying times is shown in Table 2. As can be noted from the table, prediction errors range from 2.0 hours (0.3%) to an extreme of 54.6 hours (9.6%) for Run 13. Except for Runs 5, 8 and 13, the other seven runs show only minimal errors (mean = 7.3 hrs or 1.14%). The chi-square test result (Table 2) also shows that overall results are satisfactory at 5% level of significance.

It is interesting to note the low value of the kiln factor, KF = 0.56 (Table 2), which implies a large

Table 2. Comparison of predicted and actual drying times for 10 commercial runs of predominantly 2-inch mayapis-bagtikan lumber (KF = 0.56).[1]

Run No.	Initial MC (%)	Final MC (%)	$\int Rd\overline{M} \times 0.56$ (mb-hr)	$\Sigma(\Delta h_o)_i t_i$ (mb-hr)	Actual Drying Time (hr)	Predicted Drying Time (hr)	Error (hr)	Error (%)
5	69.6	15.8	31495	33647	638.5	616.9	-21.6	3.4
6	65.1	14.1	34183	34404	661.0	659.0	-2.0	-0.3
7	57.5	14.9	31320	30668	586.0	592.5	+6.5	+1.1
8	64.1	21.2	22560	24869	590.5	559.1	-31.4	-5.3
9	61.9	16.5	29345	28050	639.0	656.6	+17.6	+2.8
10	65.8	17.7	27950	27726	685.5	688.1	+2.6	+0.4
11	67.4	16.5	30085	30356	662.5	659.3	-3.2	-0.5
12	67.2	16.1	30748	30246	663.0	668.8	+5.8	+0.9
13	59.3	17.2	27786	23771	566.0	620.6	+54.6	+9.6
14	70.9	16.8	29889	31051	683.0	669.5	-13.5	2.0

[1] Chi-square test result: $\chi^2_c = 13.62 < \chi^2_{t(0.05,\,9)} = 18.31$ based on E = 24 hours (Run 13 not included)

discrepancy between the observed and the uncorrected predicted drying time. This may be partly explained by the comparatively low kiln temperatures employed in Runs 5—14 (range: 45° — 65°C) as compared to the temperature range in Runs 1 to 4 (60° — 88°C). Low temperature kiln schedules dry lumber faster than predicted while high temperature schedules dry lumber more slowly (Bramhall, personal communication).

Model for 1-Inch Tangile-Red Lauan Lumber

Results for 1-inch thick tangile-red lauan lumber are shown in Figure 2 and Table 3. As in the previous model, the plot of the natural logarithm of R versus $\overline{M}$ is essentially linear. A combined regression analysis for three runs of tangile-red lauan (Runs 15 to 17) yields the following mathematical model:

$$-\int_{\overline{M}_1}^{\overline{M}_2} 4633 \exp(-0.0747\overline{M})\, d\overline{M} = \sum_{i=1}^{n} (\Delta h_o)_i\, t_i$$

which can be integrated as,

$$62021 \exp(-0.0747\overline{M})\Big]_{\overline{M}_1}^{\overline{M}_2} = \sum_{i=1}^{n} (\Delta h_o)_i\, t_i \quad (3)$$

This model was used to predict the drying times of Runs 15 to 17. Due to scarcity of actual kiln-drying data involving mixed charges of 1-inch tangile-red lauan, only three comparisons between predicted and actual drying times are presented for model validation (Table 3). Except for Run 15 which required more mb-hr units than predicted (error = 14.9 hrs or 10.9%), the other two runs show little discrepancy between predicted and observed drying times (mean error = 6.9 hrs or 5.2%). Result of chi-square test (Table 3) shows that the observed prediction errors are within acceptable limits.

Model for 1-Inch Mayapis-Bagtikan Lumber

The empirical relation between ln(R) and $\overline{M}$ for 1-inch thick mayapis-bagtikan lumber is graphed in Figure 3. As in the previous models, an essentially linear relation can be observed. Linear regression analysis yields the following model for 1-inch mayapis-bagtikan:

$$-\int_{\overline{M}_1}^{\overline{M}_2} 2616 \exp(-0.0542\overline{M})\, d\overline{M} = \sum_{i=1}^{n} (\Delta h_o)_i\, t_i$$

which can be integrated as

$$48265 \exp(-0.0542\overline{M})\Big]_{\overline{M}_1}^{\overline{M}_2} = \sum_{i=1}^{n} (\Delta h_o)_i\, t_i \quad (4)$$

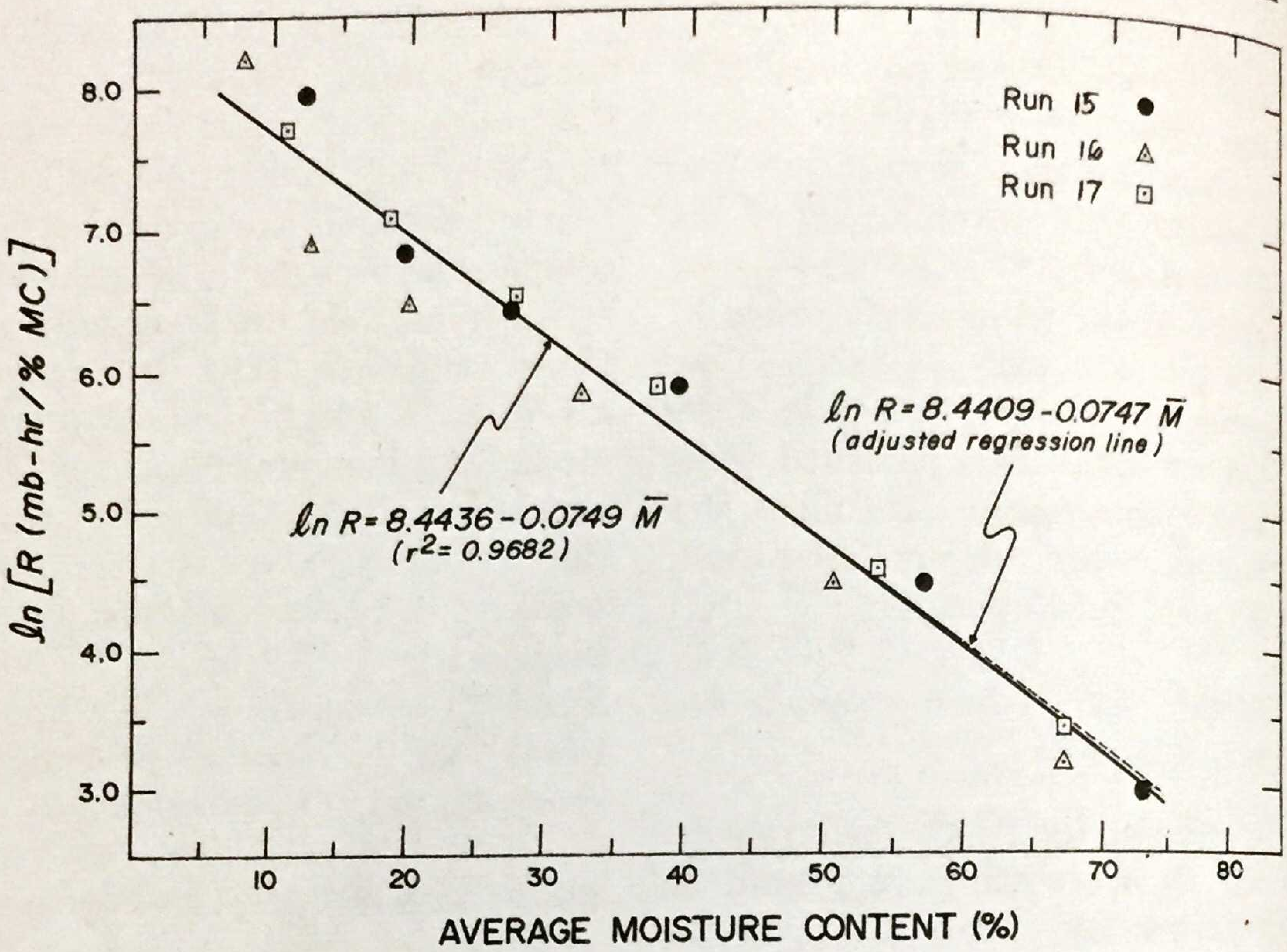

Figure 2. Natural logarithm of the resistance-to-drying (R) as a function of the average charge moisture content ($\overline{M}$) for three runs of 1-inch tañgile-red lauan lumber.

Table 3. Comparison of predicted and actual drying times for three runs of 1-inch tangile-red lauan lumber (Runs 15 to 17).[1]

Parameter	Run Number 15	16	17
Initial MC (%)	78.8	72.8	71.5
Final MC (%)	9.0	7.2	8.2
$\int R d\overline{M}$ of final MC (mb-hr)	31664	36220	33613
$\int R d\overline{M}$ of initial MC (mb-hr)	172	270	297
Net $\int R d\overline{M}$ (mb-hr)	31492	35950	33316
Actual $\Sigma (\Delta h_o)_i t_i$ (mb-hr)	38300	33434	33434
Actual drying time (hr)	136	124	124
Predicted drying time (hr)	121.1	129.5	123.7
Error (hr)	-14.9	+5.5	-0.3
Error (%)	-10.9	+4.5	-0.2

[1] Chi-square test result: $\chi^2_c = 6.73 < \chi^2_{t(0.05,\,3)} = 7.81$ based on E = 12 hours.

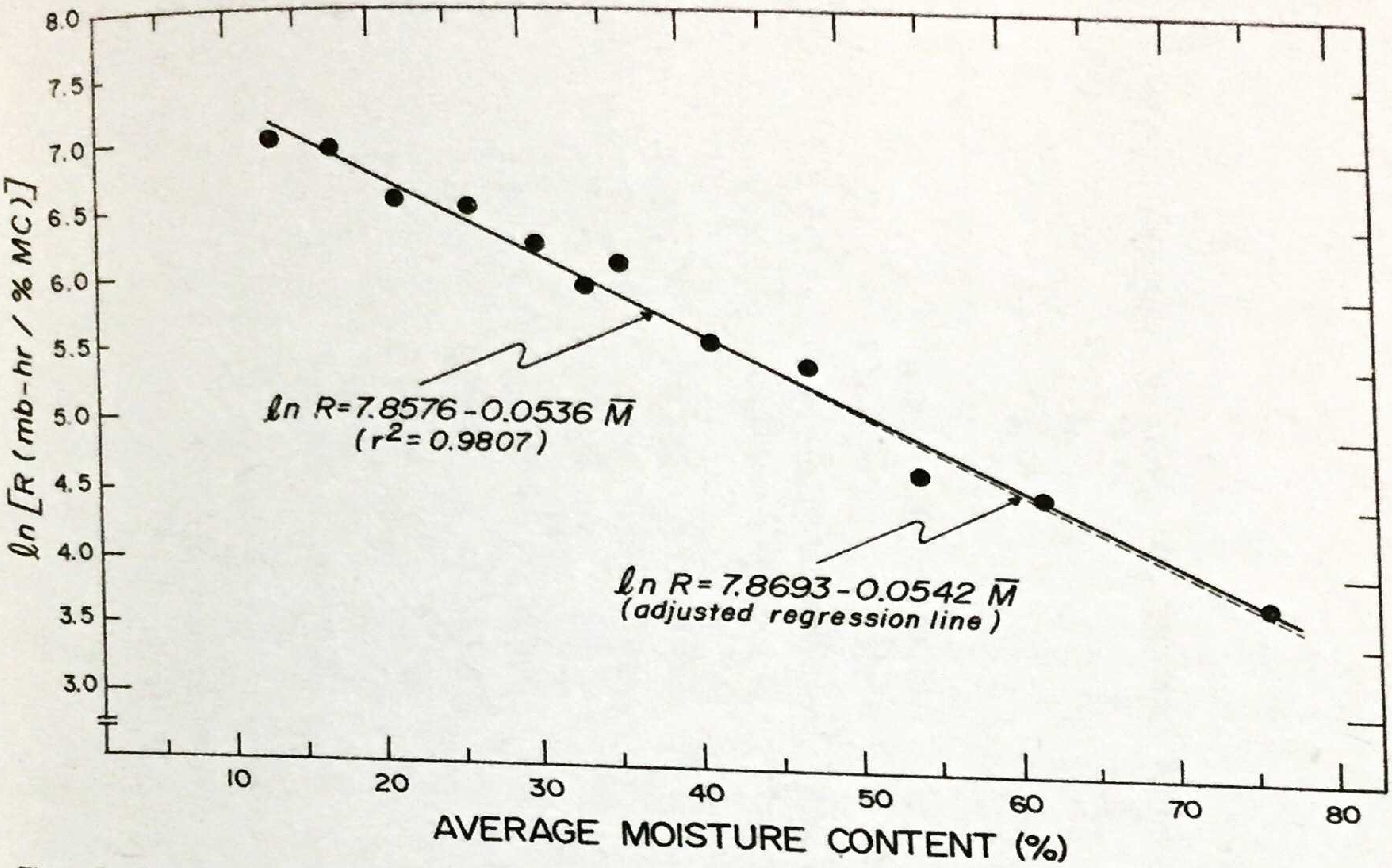

Figure 3. Natural logarithm of the resistance-to-drying (R) as a function of the average charge moisture content ($\overline{M}$) for 1-inch mayapis-bagtikan lumber.

The reliability of the above model was checked by comparing the predicted and the actual drying times in Runs 18 to 25. The summary of the comparisons is shown in Table 4. Except for Run 19, which required less mb-hrs units than predicted (error = + 31.7 hrs or 12.9%), the other seven runs (Runs 18, 20-25) show little discrepancy between predicted and observed drying times (mean error = 4.3 hrs or 1.6%). Chi-square test result (Table 4) shows that the prediction errors are within practical tolerances. The low value for the kiln factor (KF = 0.61) could again be attributed to the observation of Bramhall that the drying-effort method underestimates the rate of drying at low kiln temperatures.

In conclusion, present data support the applicability of Bramhall's method to the kiln drying of some Philippine hardword lumber species. The models presented here are best fitted to the particular species-thickness combinations tested, but it appears that they are also applicable to the kiln drying of mixed charges involving other species of comparable wood density.

Table 4. Comparison of predicted and actual drying times for eight commercial runs of predominantly 1-inch mayapis-bagtikan lumber (KF = 0.61).[1]

Run No.	Initial MC (%)	Final MC (%)	$\int Rd\bar{M} \times 0.61$ (mb-hr)	$\Sigma(\Delta h_o)_i t_i$ (mb-hr)	Actual Drying Time (hr)	Predicted Drying Time (hr)	Error (hr)	Error (%)
18	56.6	13.6	12717	12751	259.0	258.7	-0.3	-0.1
19	57.7	15.0	11767	9489	246.0	277.7	+31.7	+12.9
20	46.2	14.4	11082	11755	263.5	254.1	-9.4	-3.6
21	66.2	15.9	11618	12270	294.0	284.9	-9.1	-3.1
22	58.2	13.4	12985	13264	293.0	290.0	-3.0	-1.0
23	59.1	18.6	9547	9922	252.5	246.3	-6.2	-2.5
24	25.3	15.4	5306	5347	215.0	214.4	-0.6	-0.3
25	54.7	12.6	13353	13435	399.5	398.6	-0.9	-0.2

[1] Chi-square test result: $\chi^2_c = 5.87 < \chi^2_{t(0.05,\,7)} = 15.51$ based on E = 12 hours (Run 19 not included)

LITERATURE CITED

BELLO, E.D. 1980. Fuel reduction in kiln drying. Phil. Lumberman 26(2):17-18.

BRAMHALL, G. 1976. Semi-empirical method to calculate kiln schedule modifications for some lumber species. Wood Sci. 8(4):213-222.

BRAMHALL, G. 1979. Mathematical model for lumber drying. 1. Principles involved. Wood Sci. 12(1):14-21.

CHENG, C.C. and ARGANBRIGHT, D.G. 1981. Trials to reduce drying time of pencil slats using the drying-effort method. Forest Prod. J. 31(7):45-52.

FREESE, F. 1960. Testing accuracy. Forest Sci. 6(2):139-145.