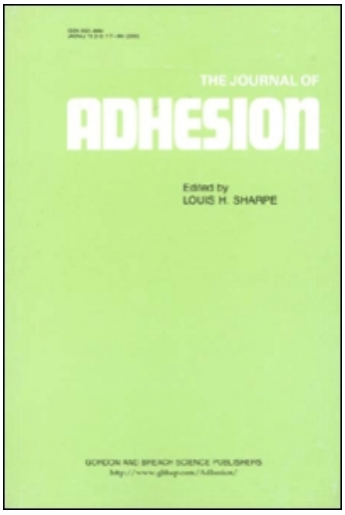

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The Response of Hardwood Flakes and Flakeboard to High Temperature Drying

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The Response of Hardwood Flakes and Flakeboard to High Temperature Drying

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This study assesses the effect of high temperature drying on chemical and mechanical properties of flakes and correlates changes in flake quality with board properties. The high temperature drying of flakes was found to have a significant effect on the internal bond (IB) of the resulting panels. The highest IB values were observed in boards produced from flakes dried at 150°C. Boards produced from flakes dried at 20°C and 350°C exhibited consistently lower values for IB. Opposite trends were noted for total acid content of flake. Multiple regression and correlation analysis revealed a strong relationship between IB, total acid content, and dryer temperature. A significant species effect was also present. Increased levels of flake total acids, acid buffering capacity, and the ratio of acid to base buffering capacities resulted in decreased board property values. Flake bending tests indicated that, in general, the strength and stiffness of the flakes were adversely affected by high temperature drying. This effect did not manifest itself, however, in the resulting panels. Possible reasons for this phenomenon are discussed.

INTRODUCTION

There is approximately 0.8 cubic feet of hardwood in Southern forests for every cubic foot of pine.[1] Since it is uneconomical to process these

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hardwood species into lumber or plywood, they have remained, to a large extent, under-utilized and thus constitute a major potential timber resource. An obvious use of otherwise unmerchantable timber is in the production of reconstituted wood products.

The performance of any wood-based composite is only as good as the bond that is formed between the adhesive and the wood substrate. Since adhesion is a physicochemical phenomenon, the strength of the glue bond is intimately related to the surface characteristics of the substrate at the time of gluing. A recurring problem in the plywood industry has been the occurrence of marginal glue bonds associated with the high temperature drying of veneers. A variety of mechanisms, both physical and chemical, have been proposed to account for this phenomenon.[2–6] Little research has been done, however, to determine the effect of high temperature drying on the strength and gluability of flakes.

Wood is a dynamic system. The physical and chemical nature of its surface will, therefore, change in response to environmental conditions. The inherent variability of wood certainly compounds the problem of analyzing the effect of environmental conditions, such as high temperature, on wood surface properties.

There are more than 150 species of wood in the United States and each exhibits unique drying characteristics.[7] Particles used in the manufacture of reconstituted wood products are generally dried to between 2 and 12 percent moisture content, depending on the type of resin employed. This means that bound water must be removed as the particles are dried below the fiber saturation point. When whole wood is dried below the fiber saturation point, both its physical and mechanical properties are affected. It is safe to assume that similar changes take place in particles during the drying process. These changes, which can alter the surface characteristics of wood, may have an even greater effect on flakes because of their large surface area-to-volume ratio.

Previous research concerning particle drying has indicated that high temperature oven-drying has adverse effects on the modulus of rupture of experimental boards.[8] It was postulated that this phenomenon could be related to changes in the chemical environment on the particle surface, which could cause problems with resin bonding. A related factor which could affect bonding efficiency is the flow of natural resins and chemicals to the particle surface at high temperatures. It is possible to adjust resin formulations to accommodate these problems, but a thorough understanding of the surface conditions and mechanisms involved is important.

A strong correlation has been found between the pH and buffering capacity of wood flour and the gelation time of urea-formaldehyde resin.[9] Other research has indicated that the insoluble or bound acid content of wood has a major catalytic effect on the condensation reaction of urea-formaldehyde.[10] The effect of high temperature drying on pH, buffering capacity, and bound and soluble acids has yet to be determined. Another area that warrants investigation is the effect of these qualities of particleboard furnish on the cure of phenol-formaldehyde resins. The objectives of this research are:

1. To investigate the chemical and mechanical effects of dryer temperature on southern hardwood flakes.
2. To correlate changes in flake quality with board properties.

MATERIALS AND METHODS

Flake preparation and drying

Flakes were produced from three different types of raw material. The wood was supplied by the U.S. Forest Service and designated by them as red oak, white oak and sweetgum, in the form of green 1 by 6 in. lumber. These woods were chosen because of their diverse chemistry and physical properties.

Prior to flake production, all boards were planed to a uniform thickness of 0.75 in. This was done to facilitate the production of uniform, high quality flakes. The lumber was then cut into 4.5 in. segments to accommodate the feeding mechanism on the flaker. Since hardwoods are notoriously difficult to flake, all raw material was placed in a vacuum-pressure soak device for 24 hours prior to flaking. The flaker employed was a 30-in. diameter disc flaker built by Washington State University. Tangentially cut flakes which measured approximately 0.75 by 2.5 by 0.020 in. were produced.

After production, all flakes were air dried to a uniform moisture content of 30%. Flakes were then randomized within each species and placed in polyethylene bags which were stored in a cooler with the temperature set at 1°C.

All flakes were then dried to a uniform moisture content of 4%. Three drying temperatures were used: 20°C, 150°C, and 350°C. The high temperature drying was conducted in a forced draft oven. After drying, the furnish was stored in polyethylene bags.

Flake bending tests

Randomly selected flakes were tested in bending to determine the effect of high temperature drying on mechanical properties. Twenty-five samples were chosen from each species and dryer temperature group. As anticipated, it was more difficult to obtain quality flakes from the two oak species than it was from the sweetgum. Enough quality flakes were produced from each species, however, to obtain a sufficient number of bending specimens.

After flakes were conditioned to equilibrium at 12% MC, small 'beams' measuring approximately 0.56 by 0.15 by 0.02 in. were cut from each flake. The excess wood remaining after the beams were cut was retained for moisture content determinations. Whenever possible the specimens were cut from the center of the flakes. This was not possible for all the oak specimens because of fractures which developed along the rays.

Flakes were tested on an Instron, using a small sample adaptor for bending developed at Washington State University.[11] The head speed was 0.01 in. per minute. Center point loading was employed and the span was 0.36 in.

The modulus of rupture (MOR) and modulus of elasticity (MOE) were determined for each flake tested. Values were corrected to the average moisture content by the following equation:[12]

$$\log S_3 = \log S_2 + (M_2 - M_3)\frac{\log\frac{S_{12}}{Sg}}{(Mp - 12)}$$

Where S_2 = the strength or stiffness value at moisture content M_2
S_3 = the corrected strength or stiffness value
M_3 = the average moisture content
S_g = the strength or stiffness value of green wood*
S_{12} = the strength or stiffness value for wood at 12 percent moisture content*
Mp = the moisture content at the fiber saturation point*

* Handbook values.

Chemical analysis

pH and Buffering Capacity

Random samples of flakes obtained from each species and dryer temperature grouping were Wiley-milled through a 2 mm screen. An aqueous wood extract was prepared by refluxing 25 g of milled wood in 250 ml of distilled water for 20 minutes. After cooling to room temperature, the mixtures were filtered through Whatman #1 filter paper with aspirator vacuum. The wood was washed twice with 100 ml increments of distilled water. The filtrate and washings were diluted to a uniform volume of 500 ml in a volumetric flask. Two separate 100 ml increments of wood extract were pipetted into 250 ml beakers. The filtrate was then titrated to a pH of either 7 or 3 with nominal 0.025N NaOH or H_2SO_4 solutions. The filtrate was constantly stirred and the pH was noted initially and after each additional increment of acid or base.

The acid buffering capacity of each solution has been defined as the number of ml of NaOH required to raise the starting pH of the wood extract to a pH of seven, times the normality of the base solution.[12] The alkaline buffering capacity was calculated as the number of ml of H_2SO_4 required to lower the starting pH of the extract to a pH of three, times the normality of the solution.

The moisture content of the wood meal used for each titration was determined and the milli-equivalents of acid or base were normalized to milli-equivalents per 100 g of oven dry wood. Two replications were run for each titration.

Bound and Soluble Acids

The soluble acid content of the wood was determined by water extraction for each species and dryer temperature used. The technique is as follows. Twenty-five g of wood meal was weighed into a 600 ml beaker. Three hundred ml of distilled water was pipetted into the beaker and kept at room temperature for 24 hours. The mixture was then filtered through Whatman #1 filter paper with aspirator vacuum. The wood meal was washed four times with 175 ml quantities of distilled water. The filtrate and washings were diluted to one liter in a volumetric flask. Two hundred ml of the extract was pipetted into a beaker and titrated with decinormal NaOH. The mixture was constantly stirred and pH readings were recorded at 120-second intervals after each subsequent addition of the base. The end point was determined as the

point where the second derivative of pH *versus* volume was equal to zero.

The total acid content of the wood was determined by sodium acetate extraction. Three hundred ml of decinormal sodium acetate solution in water was added to 25 g samples of wood meal in a beaker. The mixture was kept for 24 hours and filtered as described above. The filtrate was washed once with 175 ml of sodium acetate and three times with 175 ml increments of distilled water. The filtrate and washings were again diluted to one liter with distilled water. Two hundred ml of the filtrate was titrated with decinormal NaOH and the end point was determined as described for the soluble acid content.

The bound acid content of the wood was calculated as the total acid minus the soluble acid content. The results were normalized to values of milli-equivalents per 100 g of oven dry wood. Two replications were run for each titration.

Board Manufacture and Testing

The furnish was screened over a ¼-in. mesh prior to board manufacture to remove the fines. Boards were produced on a 50 by 50 in. laboratory press. Specific production parameters are outlined below.

Variables:

Drying temperature:	3 (20°C, 150°C, 350°C)
Species:	3 (red oak, white oak, sweetgum)
Replications:	3 (27 total boards)

Constants:

Mat size:	20 by 24 by ½ in.
Press temperature:	350°F
M.C. to press:	10%
Binder level:	6% phenol-formaldehyde
Press cycle:	7 minutes; 1 minute to stops
Density:	0.80 g/cc at 12% MC

The resin employed was an experimental phenol-formaldehyde resin designed specifically for oaks. It contained 51% solids and had a viscosity of 425 cps at 25°C. The pH of the resin was 10.75. A rotary drum type blender was employed and the atomizing pressure was 70 psi. To

insure complete resin cure, all boards were post cured overnight at 150°F. The boards were then conditioned to equilibrium at 12% MC.

After the samples had equilibrated, tests were conducted to determine internal bond (IB), MOR, MOE, and wet MOR. Two dry and two wet bending specimens and five IB specimens were cut from each board. IB was determined as outlined in ASTM D1037. Bending samples measured 3 by 18 in. Third point loading was employed with a 15-in. total span. Wet MOR is defined as a two-hour boil, one-hour cold soak, tested wet with all calculations based on the dry dimensions. The average specific gravity for all boards were 0.817. All physical and mechanical properties were normalized to this value. The normalization relationship between the individual values and the mean was determined to be linear for IB values and parabolic for all bending properties.

RESULTS AND DISCUSSION

The purpose of this research was to explore the effect of high temperature drying on a variety of flake and board properties. As a result, there was a considerable amount of data generated. A complete summary of all data is presented.

Factorial analyses of variance were performed for each dependent variable to identify the effects of species, dryer temperature, and the interaction of these independent variables. The results of these statistical tests are presented in Table I. Since the interaction of dryer temperatures and species variables was significant for most dependent variables, one-way analyses of variance were also performed for each dependent variable within each species to identify the effect of dryer temperature within each species. The results of these tests are presented in Table II. Where the one-way analyses of variance indicated a significant dryer temperature effect, Duncan's New Multiple Range Test[14] was employed to determine which temperature levels were significantly different.

Board properties

The board properties are discussed first to establish a basis for correlation with the results of the flake bending and chemical experiments. As seen in Tables I and II, the only board property that showed significant dryer temperature effect for all three species was IB. Analysis of Figure 1 indicates IB increased for all species when a dryer tem-

Table I
Results of Factorial Analyses of Variance

Dependent Variable	Source	F	Level of Significance
MOE	Species	32.849	‡
	Dryer Temperature	0.206	NS
	Species × Drier Temperature	7.251	†
MOR	Species	98.989	‡
	Dryer Temperature	1.131	NS
	Species × Drier Temperature	6.900	†
Wet MOR	Species	371.521	‡
	Dryer Temperature	1.614	NS
	Species × Drier Temperature	18.097	‡
IB	Species	168.773	‡
	Dryer Temperature	9.958	‡
	Species × Drier Temperature	6.495	†
Flake MOE	Species	8.495	‡
	Dryer Temperature	4.663	‡
	Species × Drier Temperature	2.067	NS
Flake MOR	Species	3.263	‡
	Dryer Temperature	2.924	NS
	Species × Drier Temperature	1.912	NS
Acid Buffering Capacity	Species	4816.913	‡
	Dryer Temperature	5.204	†
	Species × Drier Temperature	7.567	‡
Base Buffering Capacity	Species	17.476	‡
	Dryer Temperature	2.512	NS
	Species × Drier Temperature	4.563	†
Soluble Acid Content	Species	381.925	‡
	Dryer Temperature	48.104	‡
	Species × Drier Temperature	13.807	‡
Bound Acid Content	Species	17270.398	‡
	Dryer Temperature	48.104	‡
	Species × Drier Temperature	13.807	‡
Total Acid Content	Species	38118.057	‡
	Dryer Temperature	43.836	‡
	Species × Drier Temperature	182.462	‡

NS = Not statistically significant at 5% level.
† = Statistically significant at 5% level but not at 1% level.
‡ = Statistically significant at 1% level.

TABLE II
Results of One-Way Analyses of Variance for Dryer Temperature Effects Within Each Species

Species	Dependent Variable	F	Level of Significance
Red Oak	MOE	2.363	NS
	MOR	1.962	NS
	Wet MOR	1.304	NS
	IB	6.417	‡
	Flake MOE	3.942	†
	Flake MOR	2.761	NS
	Acid Buffering Capacity	1.603	NS
	Base Buffering Capacity	23.475	‡
	Soluble Acid Content	19.269	†
	Bound Acid Content	151.476	‡
	Total Acid Content	193.833	‡
White Oak	MOE	1.368	NS
	MOR	5.489	‡
	Wet MOR	15.321	‡
	IB	4.326	‡
	Flake MOE	0.893	NS
	Flake MOR	0.748	NS
	Acid Buffering Capacity	7.852	†
	Base Buffering Capacity	4.633	†
	Soluble Acid Content	3.651	NS
	Bound Acid Content	25.029	‡
	Total Acid Content	17.258	†
Sweetgum	MOE	0.317	NS
	MOR	0.058	NS
	Wet MOR	1.813	NS
	IB	3.516	‡
	Flake MOE	3.338	†
	Flake MOR	5.469	‡
	Acid Buffering Capacity	39.675	‡
	Base Buffering Capacity	2.981	NS
	Soluble Acid Content	38.797	‡
	Bound Acid Content	21.476	‡
	Total Acid Content	29.117	‡

NS = Not statistically significant at 5% level.
† = Statistically significant at 5% level but not significant at 1% level.
‡ = Statistically significant at 1% level.

perature of 150°C was used compared to 20°C. In the case of red oak, the difference was significant. Conversely, boards produced with flakes dried at 350°C exhibited statistically lower values than boards made with flakes dried at 150°C. Since IB is generally considered to be the best indicator of resin performance, these results indicate that

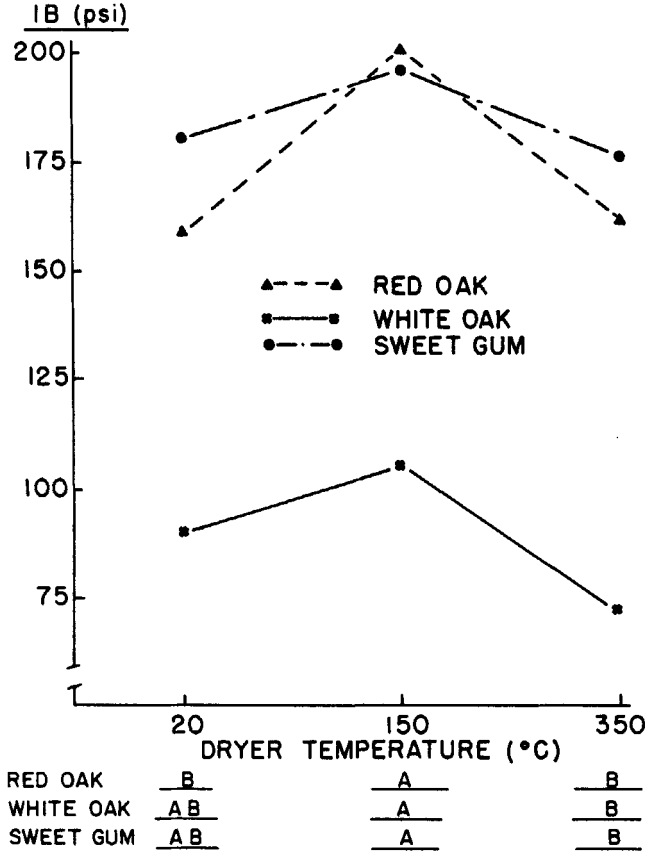

FIGURE 1 Relationship between dryer temperature and internal bond. Different letters show which values are statistically different at the 5% level as determined by Duncan's New Multiple Range Test.

the high temperature drying of flakes may indeed affect the gluability of particleboard furnish.

In general, bending properties were not significantly affected by dryer temperature. The wet MOR data, however, yielded some interesting results. As seen in Table III, the percent strength retained after testing was consistently above 50% in both red oak and sweetgum. This was not true for white oak, however. In fact, boards produced from air dried white oak flakes retained only 20% of their original strength. Another interesting observation is the fact that, for all standard

mechanical tests, the white oak boards exhibited lower property values when compared with either sweetgum or red oak, as might be expected on the basis of species density alone.

TABLE III
Average Strength Values for Boards Produced from Three Southern Hardwood Species Dried at Various Temperatures

Species	Dryer Temperature (°C)	MOE (psi × 10^{-6})	MOR (psi)	Wet MOR (psi)	Strength Retained (%)	IB (psi)
Red Oak	20	0.806	4597	2490	54	161
	150	0.891	5239	2737	52	200
	350	0.847	4962	2618	53	165
White Oak	20	0.779	3408	695	20	93
	150	0.729	3419	1143	33	105
	350	0.751	2814	1177	42	79
Sweetgum	20	0.925	5709	3561	62	182
	150	0.917	5688	3344	59	196
	350	0.953	5810	3164	55	178

Note: All bending values are averages of six observations and IB values are averages of 15 observations.

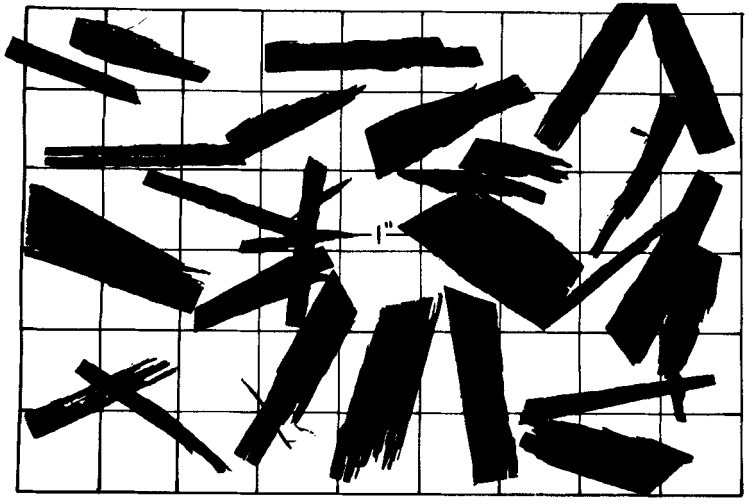

FIGURE 2 Particle geometry of disc-cut flakes produced from red oak.

FIGURE 3 Particle geometry of disc-cut flakes produced from white oak.

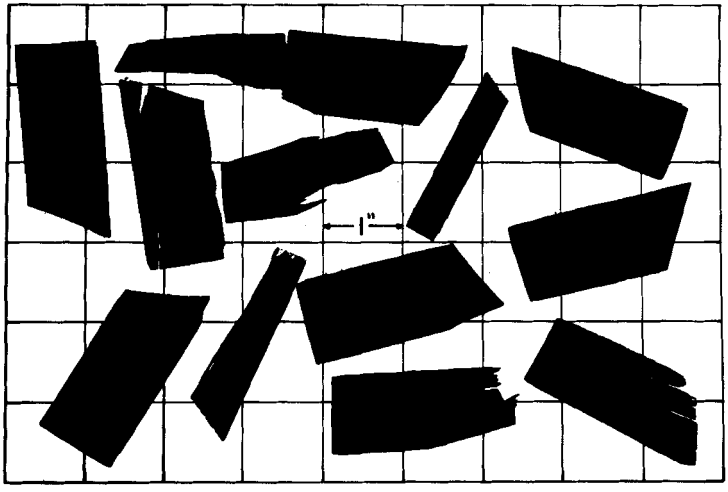

FIGURE 4 Particle geometry of disc-cut flakes produced from sweetgum.

Surprisingly, the wet MOR values for sweetgum were higher than the dry MOR values for white oak. One possible explanation for this could be the difference in the quality of flakes produced. Samples of flakes generated from each of the three species are shown in Figures 2–4. These Figures indicate that the sweetgum flakes were of a much higher quality than the flakes produced from either oak. The pictures also indicate that the red and white oak flakes suffered approximately the same degree of particle degradation during the flaking process. Flake quality may help explain the disparity in bending strength between white oak and sweetgum. It does not, however, explain why red oak, with a flake geometry similar to white oak, produced boards which were nearly as strong as the sweetgum boards. Nor can flake quality be used to explain the dramatic strength reduction of the white oak boards after the wet MOR tests.

Another factor that was explored was the possibility of density profile differences between species. To test this hypothesis, density profiles were determined for all boards tested. The density profiles for each species at the various drying temperatures are presented in Figures 5–7. Figure

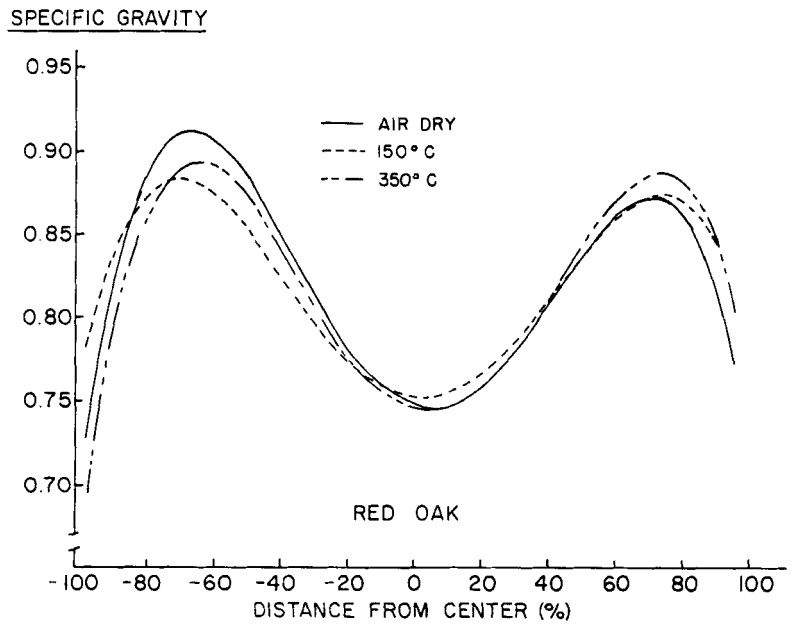

FIGURE 5 Average density profiles for red oak boards at various dryer temperatures.

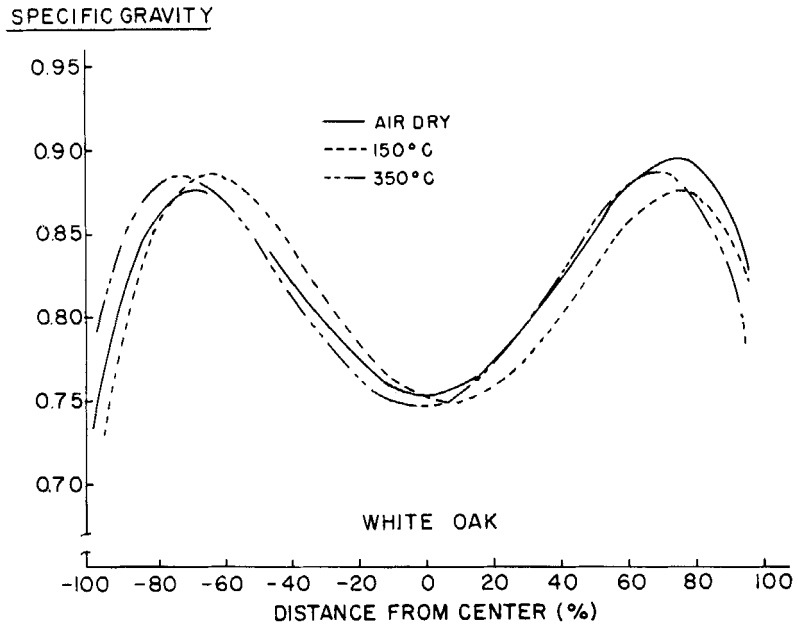

FIGURE 6 Average density profiles for white oak boards at various dryer temperatures.

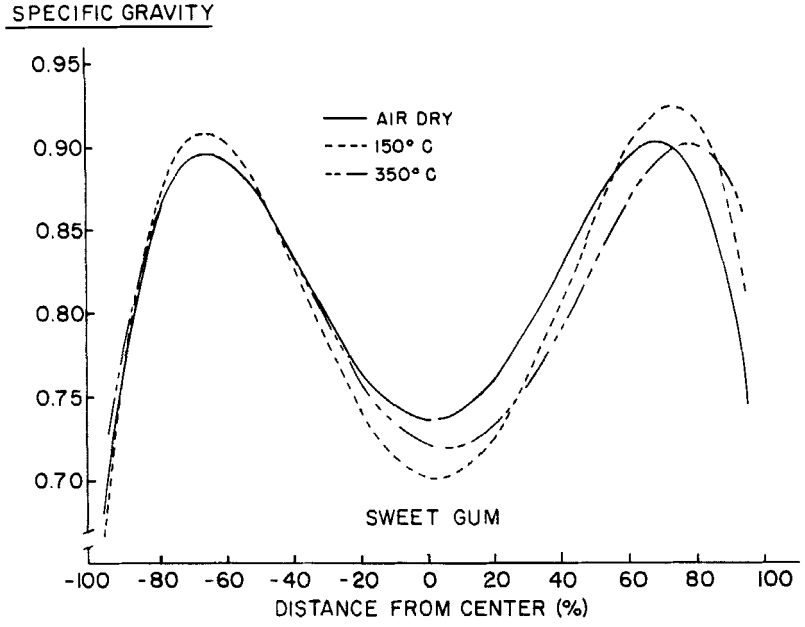

FIGURE 7 Average density profiles for sweetgum boards at various dryer temperatures.

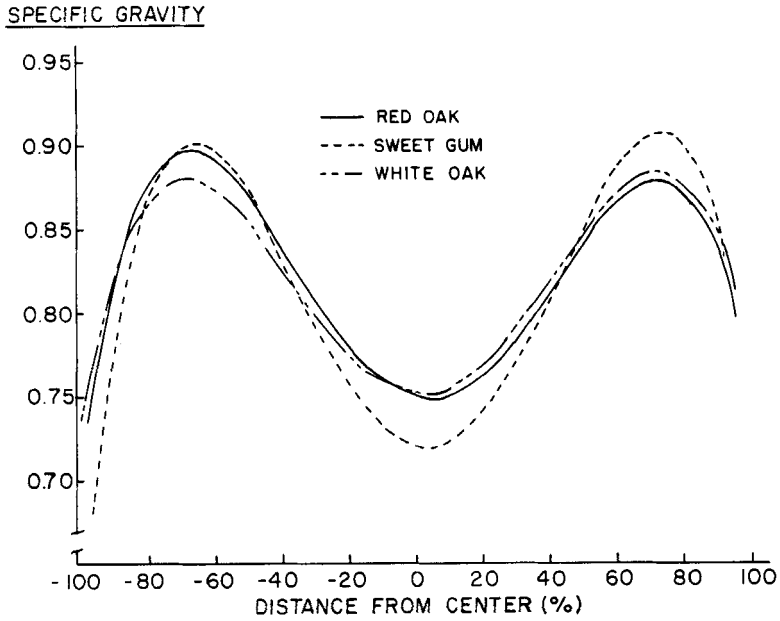

FIGURE 8 Average density profiles for boards produced from three Southern hardwood species.

TABLE IV
Average Flake Bending Properties at Various Dryer Temperatures for Three Southern Hardwood Species

Species	Dryer Temperature (°C)	MOE (psi × 10^{-6})	MOR (psi)
Red Oak	20	0.696	14776
	150	0.750	15237
	350	0.513	12757
White Oak	20	0.590	13233
	150	0.502	12023
	350	0.534	13171
Sweetgum	20	0.766	14641
	150	0.691	13401
	350	0.650	12610

Note: All values are averages of 25 observations.

8 compares the average density profiles for each of the three species. As seen in these figures, there were no significant density profile dif-

ferences either within or between species. It must therefore be concluded that some other physical or chemical phenomenon caused the differences in strength properties noted between species and within each species at the various drying temperatures.

Flake bending properties

The results of the flake bending tests are presented in Table IV. In most cases, a general trend toward decreased flake strength and stiffness with

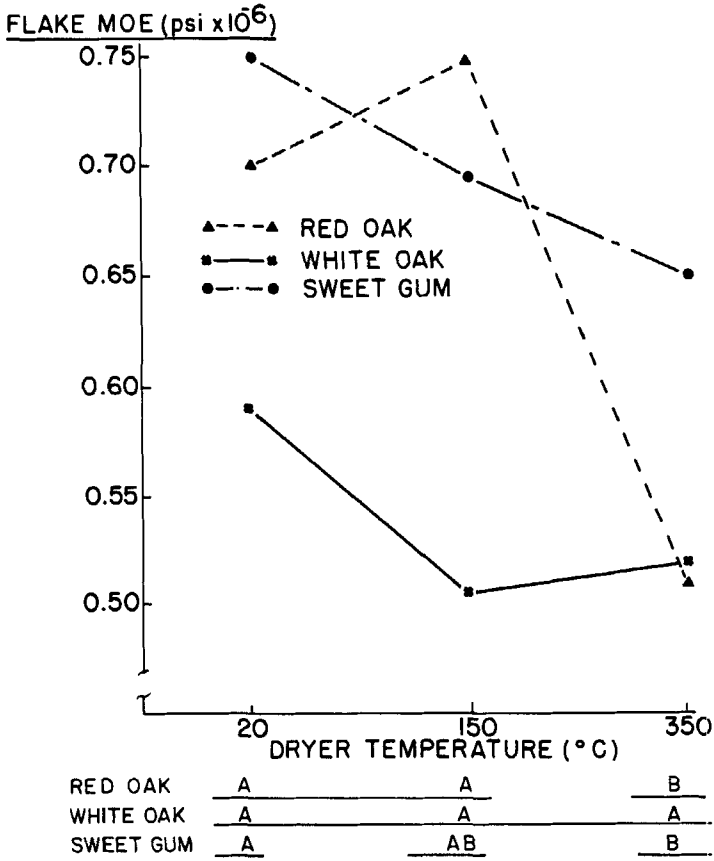

FIGURE 9 Relationship between dryer temperature and flake modulus of elasticity. Different letters show which values are statistically different at the 5% level as determined by Duncan's New Multiple Range Test.

increased dryer temperature was observed. Statistical analysis, however, indicated that only flake MOE was significantly affected by dryer temperature (Figure 9). Although the MOE values for the white oak flakes were not significantly affected by dryer temperature, flakes produced from both red oak and sweetgum exhibited significant stiffness reductions when flakes dried at 350°C were compared to those which were air dried. It is interesting to note, however, that the trends toward decreasing flake stiffness associated with high temperature drying did not manifest themselves in the resulting board properties.

Past research has indicated that the use of longer flakes tends to optimize bending properties.[15,16] The flakes used in this experiment were relatively long (2.5 in.) and had a length-to-thickness ratio of 125 : 1. The average board density was also quite high (0.817 g/cc). The combination of flake geometry and board density may have masked any adverse effects of high temperature drying on bending properties.

Chemical properties

pH and Buffering Capacity

The results of the pH and buffering experiments are presented in Table V. Statistical analysis indicated that dryer temperature had no appreciable effect on either pH or base buffering capacity. The acid

TABLE V
Average pH and Buffering Capacities at Various Dryer Temperatures for Three Southern Hardwood Species

Species	Dryer Temperature (°C)	pH	Acid Buffering Capacity (meq/100 g)	Base Buffering Capacity (meq/100 g)	Acid-to-Base Ratio
Red Oak	20	4.51	0.448	1.303	0.345
	150	4.50	0.416	1.221	0.341
	350	4.51	0.413	1.217	0.341
White Oak	20	4.46	1.468	1.328	1.106
	150	4.43	1.598	1.367	1.169
	350	4.42	1.612	1.381	1.167
Sweetgum	20	5.71	0.077	1.211	0.064
	150	5.66	0.077	1.146	0.068
	350	5.49	0.107	1.315	0.082

Note: All values are averages of two observations.

buffering capacity, as a whole, was significantly affected by drying conditions. Analysis of Figure 10 indicates that, for white oak and sweetgum, increasing dryer temperatures to 350°C resulted in increased acid buffering capacity. The acid buffering capacity of red oak was not affected by drying conditions.

Although dryer temperature did not influence the pH of the three species in question, there was a significant species effect. The pH of the sweetgum flakes was significantly higher than that of either red

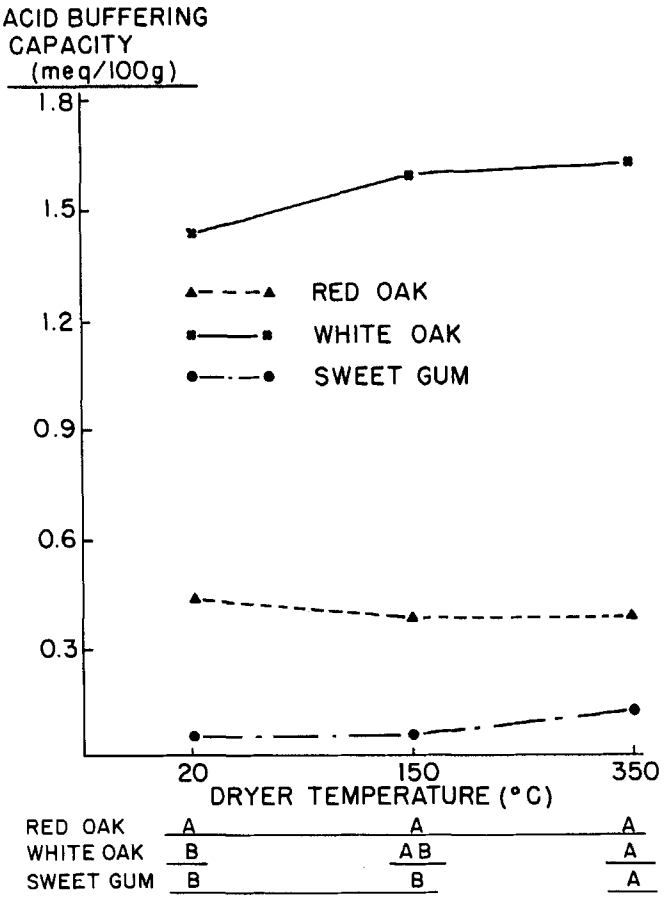

FIGURE 10 Relationship between dryer temperature and acid buffering capacity. Different letters show which values are statistically different at the 5% level as determined by Duncan's New Multiple Range Test.

TABLE VI
Results of Regression and Correlation Analysis Between Flake Chemical Characteristics and Board Properties

Independent Variable	Dependent Variable	R-Square
Soluble Acid Content	MOE	−0.817
	MOR	−0.821
	Wet MOR	−0.760
	IB	−0.750
Bound Acid Content	MOE	−0.878
	MOR	−0.914
	Wet MOR	−0.953
	IB	−0.978
Total Acid Content	MOE	−0.903
	MOR	−0.929
	Wet MOR	−0.957
	IB	−0.810
Acid Buffering Capacity	MOE	−0.848
	MOR	−0.957
	Wet MOR	−0.947
	IB	−0.908
Base Buffering Capacity	MOE	−0.507
	MOR	−0.616
	Wet MOR	−0.587
	IB	−0.684
Ratio of Acid-to-Base Buffering Capacity	MOE	−0.852
	MOR	−0.955
	Wet MOR	−0.958
	IB	−0.897
pH	MOE	0.661
	MOR	0.573
	Wet MOR	0.590
	IB	0.359

oak or white oak. The pH values for red oak and white oak, however, were not significantly different. The relatively high pH of the sweetgum furnish (about 5.5) may have been more compatible with the alkaline resin employed during this experiment. There was, however, as seen in Table VI, no strong correlation observed between pH and board properties. Since differences in board properties, both between species and within each species at the various dryer temperatures, could not be correlated to pH differences between species, it was concluded that, for the three species in question, the pH of the furnish had no significant effect on resin performance.

Although there were only slight differences noted between the base

TABLE VII
Average Bound, Soluble, and Total Acid Content Values at Various Dryer Temperatures for Three Southern Hardwood Species

Species	Dryer Temperature (°C)	Bound Acids (meq/100 g)	Soluble Acids (meq/100 g)	Total Acods (meq/100 g)
Red Oak	20	1.317	0.369	1.679
	150	1.243	0.308	1.548
	350	1.416	0.302	1.712
White Oak	20	2.451	0.508	2.958
	150	2.364	0.521	2.881
	350	2.323	0.485	2.805
Sweetgum	20	0.295	0.355	0.650
	150	0.322	0.280	0.602
	350	0.448	0.188	0.636

Note: All values are averages of two observations.

buffering capacities of the three species, considerable variation was observed between measured acid equivalents. It is also of interest to note that white oak, which consistently produced boards with lower property values, was the only species which had an acid-to-base equivalent ratio greater than one.

Bound and Soluble Acids

The results of this phase of the experiment are presented in Table VII. Statistical analysis (Tables I and II) indicated that all three parameters—bound, soluble, and total acid content—showed significant dryer temperature effects. With the exception of the soluble acid content for white oak, significant dryer temperature effects were also noted for all parameters within each species.

The interaction between dryer temperature and bound acids is seen in Figure 11. In all three species, bound acid levels for flakes dried at 150°C were either lower than or equal to air-dried flakes. Both red oak and sweetgum showed significant increases in bound acid levels for flakes dried at 350°C. White oak showed no significant increase at higher drying temperatures. It should be noted, however, that at all dryer temperatures, white oak had consistently higher bound acid levels than either red oak or sweetgum.

Slightly different trends were observed for soluble acid content (Figure 12). Maximum soluble acid levels for red oak and sweetgum were observed in flakes which had been air dried. Increasing dryer

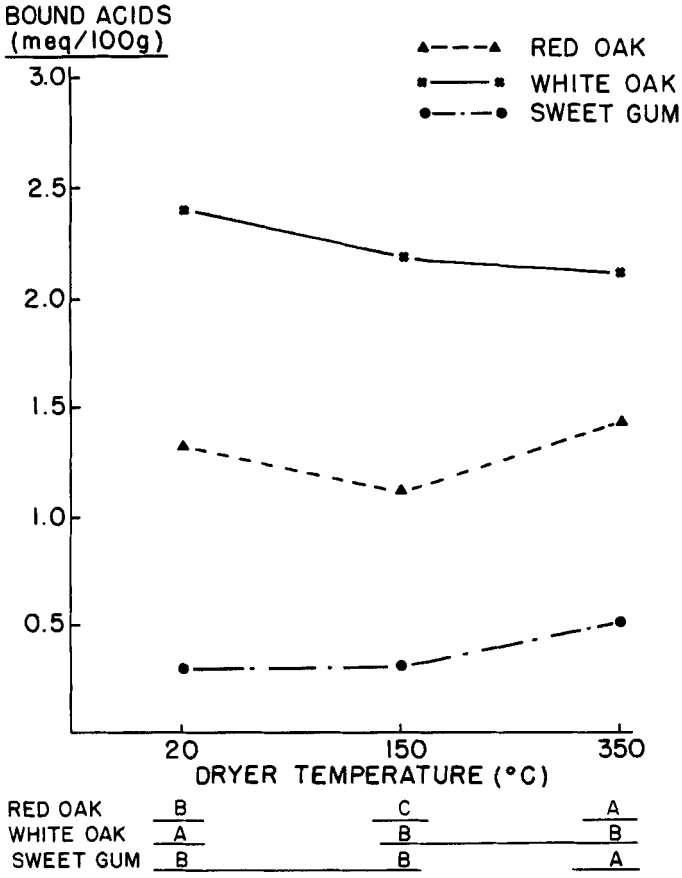

FIGURE 11 Relationship between dryer temperature and bound acids. Different letters show which values are statistically different at the 5% level as determined by Duncan's New Multiple Range Test.

temperatures to 150°C resulted in a significant decrease in soluble acids for both species. Further increases in dryer temperature produced either no change or a further decrease in soluble acids. The soluble acid content of white oak was not significantly affected by dryer temperatures, but once again it exhibited consistently higher values than either red oak or sweetgum.

As seen in Figure 13, total acid levels for red oak and sweetgum also decreased when samples dried at 150°C were compared to those

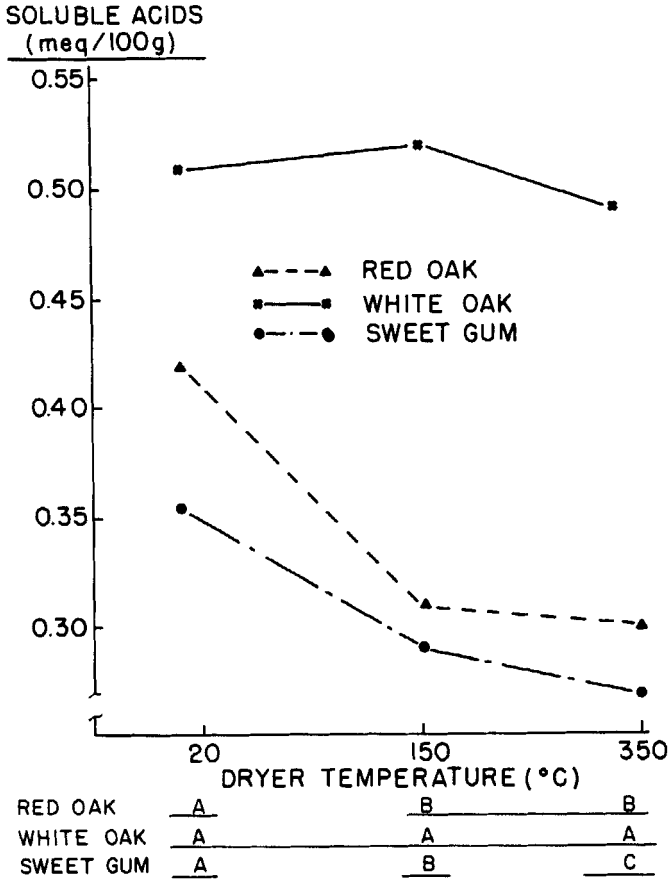

FIGURE 12 Relationship between dryer temperature and soluble acids. Different letters show which values are statistically different at the 5% level as determined by Duncan's New Multiple Range Test.

which were air dried. Further increases in dryer temperature were accompanied by significant increases in total acid levels for both species. It is appropriate here to compare these facts with the IB results presented in Figure 1. In general, IB values initially increased with dryer temperatures of 150°C and then significantly decreased with more severe drying. The total acid content of both red oak and sweetgum exhibited just the opposite tendencies. This suggests that the total acid content of the furnish may have an effect on bond performance. The fact that

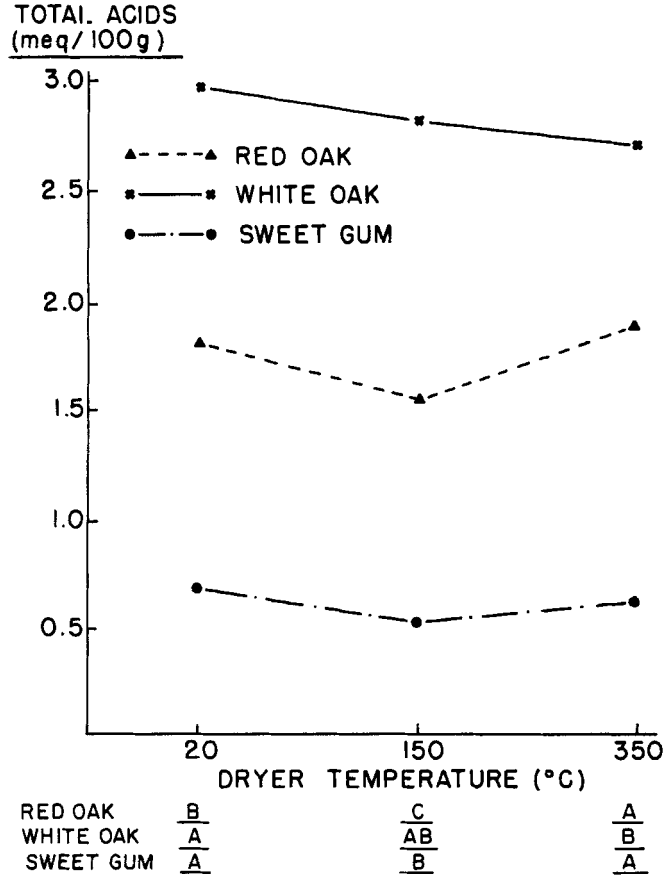

FIGURE 13 Relationship between dryer temperature and total acids. Different letters show which values are statistically different at the 5% level as determined by Duncan's New Multiple Range Test.

both IB and total acid content were influenced by dryer temperature seems to indicate that board properties may be influenced by furnish drying schedules. Another interesting observation is the fact that flakes which were dried at 150°C generally had lower levels of bound, soluble, and total acids than flakes which were air dried. This indicates that there might be an optimum dryer temperature that will minimize acid levels and maximize board properties.

The interaction of dryer temperature and IB was basically the same

for all three species. Trends in acid content for white oak, however, were slightly different from those noted for red oak and sweetgum. Although there was a general decrease in acid levels when flakes dried at 150°C were compared to those which were air dried, no substantial increase was observed at the higher drying temperature. It may be that the amount of total acids present was the over-riding factor. It should be noted that, at all drying temperatures, white oak flakes exhibited nearly twice the total acid levels of red oak and over four times those of sweetgum.

Multiple regression and correlation analysis was used to test the apparent relationship between IB, total acid content, and dryer temperature. Values for all three species were employed and IB was plotted as a function of both dryer temperature and total acid content. The response surface generated is presented in Figure 14. The r-square value was 0.987 which indicates that there is, indeed, a strong correlation between dryer temperature, total acid content, and IB.

Species effects

Analysis of Table I indicates that there was a highly significant species effect present during every phase of this study. This was not surprising. It was interesting, however, to note the regularity of ranking when comparisons were made between species. When the mechanical properties of the boards were analyzed, the following was observed: sweetgum > red oak > white oak. This trend was reversed, however, when the results of the chemical tests were considered, where for total acid content, bound acid content, soluble acid content, acid buffering capacity, and basic buffering capacity white oak > red oak > sweetgum.

Linear regression and correlation analyses were performed to test the significance of relationships between flake chemical properties and board mechanical properties. Table VII shows the results of these analyses, performed on pooled data of the three species. The data indicate that the total acid content, acid buffering capacity, and the ratio of acid-to-base buffering capacity of the flakes had the most significant effect on board properties. The fact that the regression lines all had negative slopes implies that increased acid levels are directly related to decreases in board strength. This result confirms observations made in the preceding section.

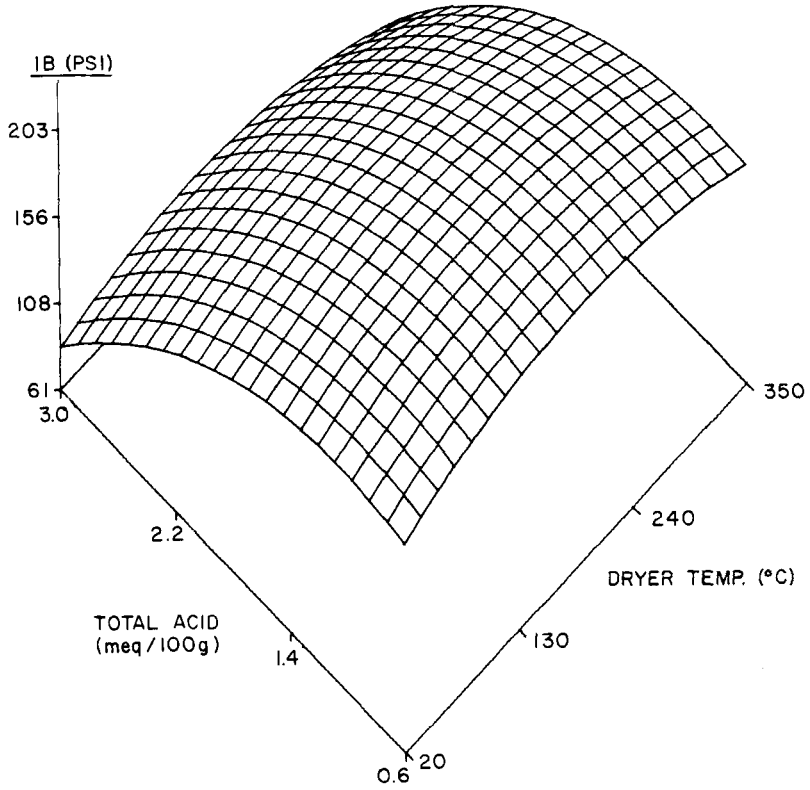

FIGURE 14 *Relationship between internal bond, total acid content, and dryer temperature for all species* ($r^1 = 0.987$).

SUMMARY

The objectives of this experiment were to investigate the chemical and mechanical effects of dryer temperature on Southern hardwood flakes and to correlate changes in flake quality to board properties.

The results of the flake bending tests indicated that there was a general trend toward decreasing strength and stiffness with increasing dryer temperature. The differences noted in flake mechanical properties could not be correlated to board properties, however.

The chemical tests, however, yielded some interesting results. When all boards were considered, regardless of dryer temperature, a strong correlation was observed between board properties and flake total acid

content. Similar trends were noted when the acid buffering capacity and the ratio of the acid-to-base buffering capacities were considered. It was found that increased acid content resulted in a decrease in board properties. There was a significant species effect here. Sweetgum, which had the lowest total acid content, consistently had the highest board properties, whereas white oak, which consistently produced lower quality boards, always exhibited the highest total acid levels. Boards produced from white oak were the only ones which retained less than 50% of their strength after a two-hour boil and one-hour cold soak. It is interesting to note that white oak was also the only species with an acid-to-base buffering capacity ratio greater than one. Since a highly caustic phenol-formaldehyde resin was employed, the changes in flake chemical properties which were noted may have had an adverse effect on resin cure. This observation parallels the theory of adhesion initially formulated by Bikerman,[17] who proposed the existence of a weak boundary layer in limiting adhesive performance.

The effect of dryer temperature on total acid content was highly significant. Moderate drying schedules resulted in a decrease in total acid content. The lowest acid content was observed in flakes dried at 150°C. The total acid content of air dried flakes was approximately equal to that of flakes dried at 350°C; both generally exhibited higher total acid levels than flakes dried at 150°C. Past research has indicated that the acidity of oak extractives has an adverse effect on the bonding efficiency of phenol-formaldehyde resins.[18] While this may help explain the relationship between acid content and board properties seen in Table VII, it does not explain why dryer temperature affected the total acid content.

Chow[19] noted a correlation between the intensity of the 1730 cm^{-1} band in the infrared spectra of wood and the onset of surface inactivation due to drying. He observed an initial decrease in intensity for this band, regardless of temperature, followed by a rapid increase. The 1730 cm^{-1} band is associated with the carbonyl absorption of carboxyl and ester groups. The initial decrease was attributed to a loss of ester and carboxyl groups while the increase was associated with oxidative carboxylation. Further research would be needed to determine the relevancy of Chow's observations to the trends noted here, but the parallels are fascinating.

As seen in Figure 14, IB values were directly correlated to both total acid levels and flake drying temperature. It is apparent that there is an optimum dryer temperature, between air dry and 350°C, that will

minimize total acid content and thereby maximize resin performance. Similar trends were not observed for static bending properties. Flake length was probably the dominant factor here and, in light of the chemical and IB results, it is quite possible that the use of a different flake geometry may have yielded quite different results. This is another area that certainly warrants future consideration.

The different strength values observed between species might have been related to species density differences. There was, however, a significant dryer temperature effect within each species group. This dryer temperature effect was directly related to the total acid content within species group. The excellent correlation between physical properties and various chemical factors (Table VI) suggests that wood chemistry is a very important factor in bonding efficiency. Differences in species density could not account for differences in IB with dryer temperature. Thus the contribution of differences in species density must play a secondary role in bond performance within the framework of this experiment.

CONCLUSIONS

1. Dryer temperatures of 350°C generally resulted in significant decreases in flake bending properties. These decreases were not observed in the resulting boards, however.
2. The high temperature drying of flakes had an adverse effect on the IB values for all species.
3. Increases in total acid content, acid buffering capacity, and acid-to-base buffering capacity ratios can be directly correlated to decreases in board strength properties.
4. There is a strong correlation between total acid content, dryer temperature, and IB.

Acknowledgement

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