
**CRITICAL LITERATURE
REVIEW OF
RELATIONSHIPS
BETWEEN
PROCESSING
PARAMETERS
AND PHYSICAL
PROPERTIES
OF
PARTICLEBOARD**



**USDA FOREST SERVICE
FOREST PRODUCTS LABORATORY
GENERAL TECHNICAL REPORT
FPL-10
1977**

**U.S. DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
MADISON, WIS.**

**CRITICAL LITERATURE REVIEW
OF RELATIONSHIPS
BETWEEN PROCESSING PARAMETERS
AND PHYSICAL PROPERTIES
OF PARTICLEBOARD**

by
MYRON W. KELLY

GENERAL TECHNICAL REPORT FPL-10
May 1977

Prepared for
Forest Products Laboratory
Forest Service
U.S. Department of Agriculture

Kelly is a member of the faculty of the
Department of Wood and Paper Science
School of Forest Resources
North Carolina State University, Raleigh

ABSTRACT

The pertinent literature has been reviewed, and the apparent effects of selected processing parameters on the resultant particleboard properties, as generally reported in the literature, have been determined. Resin efficiency, type and level, furnish, and pressing conditions are reviewed for their reported effects on physical, strength, and moisture and dimensional properties.

A serious deficiency in the research appears to be lack of consideration of the within-panel density gradient and its effects on physical properties.

ACKNOWLEDGMENTS

The author wishes to acknowledge the financial assistance provided for this work by the Forest Service of the United States Department of Agriculture and the National Particleboard Association, Silver Spring, Maryland. The assistance provided by the personnel at the Forest Products Laboratory in Madison, Wisconsin is also appreciated.

Forest Products Laboratory is maintained by the U.S. Department of Agriculture, Forest Service, in cooperation with the University of Wisconsin, Madison.

TABLE OF CONTENTS

	Page
LIST OF FIGURES.....	IV
INTRODUCTION.....	1
PHYSICAL PROPERTIES.....	2
Density.....	2
Vertical Density Gradient.....	4
Formaldehyde Release.....	16
Springback.....	20
Surface Characteristics.....	23
PROCESSING PARAMETERS.....	23
Resin Efficiency.....	23
Adhesive Type and Level.....	27
Furnish.....	29
Pressing Conditions.....	32
Mat Moisture Content.....	32
Press Closing Rate.....	33
Press Time, Temperature, and Pressure.....	34
STRENGTH PROPERTIES.....	36
Bending Strength.....	37
Modulus of Rupture.....	37
Density.....	37
Particle configuration and orientation.....	39
Modulus of Elasticity.....	41
Density.....	41
Particle configuration and orientation.....	42
Internal Bond.....	44
Other Strength Properties.....	45
MOISTURE AND DIMENSIONAL PROPERTIES.....	46
Equilibrium Moisture Content.....	46
Dimensional Properties.....	48
Water Absorption and Thickness Swelling.....	49
Density.....	50
Particle configuration.....	53
Resin and wax.....	54
Linear Expansion.....	55
Density.....	55
Particle configuration.....	56
Resin and wax.....	57

LIST OF FIGURES

Figures	Page
1. Vertical density gradient of a three-layer particleboard	5
2. Internal bond variation with thickness for a three-layer particleboard	6
3. Influence of initial moisture content and press time on the core temperature with the granular-type particle mat (SG 0.65).	9
4. Influences of initial moisture content and press time on the core temperature with the flake-type particle mat (SG 0.75)	10
5. Moisture distribution in particle mats as influenced by press time	12
6. Relationship between initial moisture content and the press time at which the core temperature rises above 100° C for the granular-type particle	13
7. Effect of various moisture and temperature conditions on vertical density gradients in 0.5-inch particleboard	15
8. Influence of heating temperature on residual formaldehyde	18
9. Influence of particleboard moisture content on residual formaldehyde	19
10. Thickness springback as influenced by flake dimensions	21
11. Influence of resin droplet size on tensile strength perpendicular and parallel to particleboard surface	25
12. Relationship between wood density and modulus of rupture for four particleboard densities	38
13. Relationship between specific gravity and modulus of elasticity of particleboard face layers	43
14. Absorption isotherms for particleboards compared to wood, at 70° F	47
15. Relationship between thickness swelling and moisture content increase	50
16. Influence of particleboard density on rate of thickness swelling.....	52

CRITICAL LITERATURE REVIEW OF RELATIONSHIPS BETWEEN PROCESSING PARAMETERS AND PHYSICAL PROPERTIES OF PARTICLEBOARDS

by
MYRON W. KELLY

INTRODUCTION

The development of the particleboard industry has been characterized by large and dramatic changes in equipment, resins, and levels of automation since its inception in the early forties. The large number of processes currently used by the industry to produce flat-pressed particleboard all have similar manufacturing steps. Subtle equipment and processing modifications to circumvent patents, as well as improvements based on experience with earlier plants, have practically guaranteed that no two plants are exactly the same. While specific methods may vary from plant to plant, they all have particle preparation, drying, and screening steps, as well as resin application, mat formation, hot pressing and edge trimming stations. A detailed development of manufacturing processes can be found in Kollmann *et al.* (1975).

The particleboard literature contains results of thousands of research projects conducted by many researchers over the past forty years. A large portion of this literature is in German or Russian publications, many of which are unavailable. Consequently, this review is based primarily on research published in the English literature with only a few references to untranslated foreign papers.

The total number of particleboard-related publications is overwhelming, as is evident by quickly scanning the "Particleboard and Related Structural Panel Products" section of the *Abstract Bulletin of the Institute of Paper Chemistry* and other abstracting services. Restriction of this review to the effects of various processing parameters on panel properties reduced the number of applicable publications to a more manageable number. However, this is not to imply all pertinent

publications were reviewed, although none that were applicable and useful were intentionally excluded.

The difficulty encountered in a review of this nature is attempting to develop a relationship between a processing parameter and specific particleboard properties from the large number of reports and the wide range of experimental conditions represented by these reports. Initially, efforts were made to quantify the effect of processing parameters on the properties of the resultant particleboard--e.g., the influence of flake length on the bending strength and dimensional stability of the board. This proved to be a futile exercise because of the interaction of other processing variables and the wide range of experimental conditions used by the various researchers. Consequently, this report qualitatively presents the reported relationships between processing variables and the resultant particleboard properties.

The pertinent literature has been reviewed and the apparent effects of selected processing parameters on the resultant particleboard properties, as generally reported in the literature, have been determined. Emphasis has been placed on the literature in which strength and dimensional properties, as influenced by processing parameters, have been studied. However, the initial portion of the report is devoted to a review of general particleboard properties and processing parameters. A number of reports emphasize these general properties and contain much useful infor-

¹This is Paper No. 5065 of the Journal Series of the North Carolina Agricultural Experiment Station, Raleigh.

mation. The individual reports are reviewed in some detail within the respective sections of this review. Not all investigators agree as to the effect of a given processing variable on the resultant panel properties; however, in many instances these disputes can be explained by differences in experimental conditions. In many other instances, further research is necessary to obtain more information before the contradictory findings can be resolved.

A few general comments on the particleboard literature are possible from a review of this nature. The most obvious deficiency throughout the literature, with a few notable exceptions, is the lack of detailed experimental procedures in the published reports. In some extreme cases the experimental details consisted only of a statement that particleboard was made in the laboratory, with no details as to particle type, adhesive content, or pressing conditions. Fortunately, this example is not representative; more information is normally given. However, lack of detail on pressing conditions, such as mat moisture content and press closing rate, is widespread in the literature. It is hoped that this deficiency will be remedied in the future.

Another unfortunate characteristic is the practice of reporting board density figures with no details of the moisture content at which it was determined. The nonuniformity of test methods for water absorption and dimensional stability also effectively limits comparisons between reported values of individual researchers.

By far, the most serious deficiency in the particleboard literature is the lack of emphasis on the vertical density gradient. Innumerable articles appear in which results reportedly show the effect of processing parameter changes on the board physical properties. Unfortunately, these parameter changes may influence the vertical density gradient also, but this remains undetected because the gradient, too often, is not determined. Much more valid relationships between processing parameters and board properties could be obtained if the vertical density gradients were determined. It is hoped that both the vertical density gradient and the moisture content gradient will eventually be routinely determined by all researchers.

The above criticisms are not meant as a blanket indictment of the particleboard literature. A tremendous volume of useful information pertaining to particleboard manufacture and properties is available, and more is added daily. The rapid growth of this industry was possible only with the information and knowledge acquired through the excellent research conducted by many investigators. Further advances, in both processing and applications, will also be realized with continued research efforts of many individuals.

Comments and criticisms which are applicable to more than one section in the report have been included in all pertinent sections. This results in duplication in the respective areas but the usefulness of the report to prospective readers may be enhanced by this method of presentation.

PHYSICAL PROPERTIES

Various particleboard physical properties are not readily classified as either strength or hygroscopic characteristics, but are important for most particleboard applications. Many of these properties, such as density, vertical density gradient, and springback, have a significant influence on the resultant strength and hygroscopic characteristics of the particleboard panel. However, these, as well as formaldehyde release and surface characteristics, are also dependent upon processing parameters such as pressing conditions, resin content, and particle geometry. It will be helpful to develop these physical properties in this section and various processing parameters in the next section before discussing the interdependent effects of physical properties and processing variables on the strength and hygroscopic characteristics of particleboard.

Density

The two most important factors controlling the average final density of a particleboard are the raw material density and the compaction of the mat in the hot press. Any change in one of these factors requires an adjustment of the other if the average board density is to remain constant. Likewise, either of these factors can be changed to increase or decrease the average particleboard density. However, a higher density panel produced by increasing the compaction level will not have properties equal to the same-density panel produced with higher density wood furnish. This is only one example of the interdependence of processing parameters on the properties of the resultant particleboard. Isolation of the effect of individual processing para-

meters on particleboard properties is extremely difficult and can, at best, be only approximated.

The pressing operation consolidates the particle mat to the desired thickness and polymerizes the binder system between individual particles. The first function eliminates many of the voids in the mat and compresses the wood structures; the latter function ensures retention of the consolidated mat upon release of the pressure. The amount and condition of the material in the mat, together with the pressing techniques, determine the average resultant board density. Thickness control of most particleboard production is attained by using "stops": Incompressible material of the appropriate thickness is placed on two sides of each press opening and the platens are closed against these stops, resulting in a gap between the two platens equal to the desired particleboard thickness.

The maximum pressure employed for particleboard in a press equipped with stops controls the rate of press closing, assuming the pressure exceeds the minimum required to compact the mat to the desired thickness. The rate of press closing on a given weight of wood furnish does not affect the average final particleboard density. That density is independent of the pressing operation when the press temperature and pressing time are sufficient to polymerize the adhesive system and allow evaporation of the excess water. The average particleboard density is dependent upon the quantity and density of the wood furnish used to make a particleboard of a given thickness, but the maximum pressure--and hence the rate of closing to stops--has an extremely critical effect on the vertical density gradient, as shown in the next section.

The final average density of particleboard is dependent not only upon the amount of woody material in the mat but also upon processing conditions prior to the pressing operation--specifically, furnish species, preparation and drying, adhesive content, and other additives.

The literature contains many examples in which the specific gravity or density is stated ambiguously; a reported panel density of 45 lb/ft³ (pounds per cubic foot) is inadequate. For example, this could mean 45 pounds of oven-dry particleboard per one cubic foot of dry particleboard, or 45 pounds of oven-dry particleboard per one cubic foot of particleboard at any moisture content, or it could even mean 45 pounds of particleboard and water per one cubic foot of particleboard at any moisture content. Consequently, the equi-

ilibrium moisture content (EMC) at which the volume and weight are determined for the density calculation must be specified. Specific gravity is always calculated with the oven-dry weight in the numerator but the EMC at which the volume is determined for the denominator must also be specified. Therefore, a density of 45 lb/ft³ (oven-dry weight, volume at 12 percent moisture content) is the same as a specific gravity of 0.721 (oven-dry weight, volume at 12 percent moisture content) and also the same as 50.5 lb/ft³ (weight and volume at 12 percent moisture content). Clearly, more care should be exercised in the reporting of board density and specific gravity.

Unless specifically stated in this report, the densities quoted from the literature sources are at unspecified moisture contents, as the required information is not contained in the original report.

The effect of furnish species on particleboard physical properties is primarily related to the wood density and the necessity of compressing the wood to obtain satisfactory particleboard. In general, a conventional particleboard with a density lower than the density of the wood furnish will be unsatisfactory (Larmore 1959; Lynam 1959; Suchsland 1967; Hse 1975). The compaction of the mat to an average density higher than the density of the furnish will allow better surface contact between the component particles of the mat. This results in better adhesive utilization because more adhesive-coated particles will be in intimate contact with other wood particles instead of with voids.

Suchsland (1959) developed a statistical model for a particleboard mat relating the degree of densification to particle geometry, relative air volume, and component wood density. The distribution of total particle thickness varies randomly in a mat; regions of high total particle thickness will obviously be compressed to a greater extent than will corresponding regions of low total particle thickness when the entire mat is compressed to a given uniform thickness. Suchsland further determined that relative compression area--not the more commonly accepted board density--is the significant factor in developing bending strength in a flakeboard.

However, board density and area of compaction are directly related for mats containing different amounts of a given species of the same particle configuration and pressed to constant thickness. Larmore (1959) has shown that the modulus of rupture for particleboard of specific gravity 0.73 (oven-dry weight, volume at 75°F and 65 percent relative humidity)

is higher for aspen furnish (specific gravity 0.37, oven-dry weight, green volume) than for yellow birch (specific gravity 0.65, oven-dry weight, green volume). Larmore also reported extremely low modulus of rupture values for particleboard made with yellow birch furnish to a specific gravity of 0.56 (oven-dry weight, volume at 75° F and 65 percent relative humidity), lower than its component species. This further illustrates the necessity of compressing the wood to some extent to obtain satisfactory board properties.

Obviously, at some high specific gravity the effect of the furnish specific gravity on the resultant board strength properties should disappear, since the board specific gravity has a theoretical maximum equal to the specific gravity of the wood substance. However, for medium- to high-density particleboard, woods of specific gravity below that of the finished board will result in a more satisfactory product.

Density of the raw material furnish is the most critical parameter when determining the potential of a given species for particleboard manufacture. The literature contains references to this interaction by noting an improvement in resin efficiency when either using woods of lower specific gravities to produce particleboard of constant final specific gravity or using a constant wood specific gravity and producing boards with higher final specific gravities (Burrows 1969; Hann *et al.* 1962; Lehmann 1970; Shuler 1974; Hse 1975). These all indicate the necessity of compressing the wood particles to a higher specific gravity than the original wood to attain sufficient interparticle contact and allow the use of a lower adhesive level than would otherwise be required.

The literature appears to be devoid of other species effects in relation to particleboard specific gravity. This is not surprising; extractive content, acidity, grain deviation, and other species characteristics should have a negligible influence on the final board specific gravity.

The oven-dry specific gravity of a particleboard can be readily controlled and accurately calculated from the dry weight of wood and other additives used to produce a mat of specified volume. However, higher density particleboard will have a significant effect upon the press cycle--more wood has to be heated, more water removed, and more adhesive reacted (Heebink *et al.* 1972).

The particle configuration should, like some species effects, have a negligible effect on the final specific gravity, assuming the applied pressure is sufficient to compress the

mat to the desired thickness. Suchsland (1959) reported a higher pressure required to reach a desired specific gravity for narrower and thicker flakes as opposed to wider and thinner flakes.

The particle moisture content entering the press also fails to influence the average oven-dry specific gravity of the final particleboard, but the moisture content effect on the vertical density distribution is highly significant, as will be shown in the next section. Because the compressive strength of wood is inversely related to the moisture content, the pressure required to compress the mat to a given thickness will be lower as the moisture content increases. However, an elevated moisture content significantly extends the total press time: excess moisture has to be removed from the mat before the adhesive will cure and before the danger of delamination due to steam release at the time of press opening is reduced.

Vertical Density Gradient

The density of a mat-formed hot-pressed particleboard is not uniform in the thickness (vertical) direction, but varies through the thickness. The density profile of a board is highly dependent upon the particle configuration, moisture distribution in the mat entering the press, rate of press closing, temperature of the hot press, reactivity of the resin, and the compressive strength of the component wood particles. The effect of these variables on the vertical density gradient will be examined in this section.

The vertical density gradient in particleboard substantially influences many strength properties, as adequately demonstrated by numerous studies found in the literature. However, much more numerous in the literature are reports in which the vertical density gradient and its influence on particleboard properties are completely ignored. Certain properties, most notably bending strength, are significantly enhanced by the presence of this vertical density gradient while other properties, such as tensile strength perpendicular to the panel surface and interlaminar shear, are adversely affected by this density distribution. Therefore, depending upon which properties are most critical in the ultimate application of the panel, modifications of the pressing procedure may be justified either to enhance or to restrict the formation of this gradient.

Shen and Carroll (1970) studied the vertical density gradient and vertical layer strength as determined by the torsion shear technique (Shen and Carroll 1969). The torsion shear strength was linearly correlated for 12 com-

mercial boards, indicating a potential application of the torsion shear test as a method for determining the vertical density gradient.

Plath and Schnitzler (1974) have recently shown the high correlation between vertical density gradient and tensile strength perpendicular to the panel surface. The standard test specimen for tensile strength perpendicular to the surface consists of the entire board thickness (ASTM 1975); consequently, rupture will occur at the weakest point in the thickness direction. Plath and Schnitzler determined the tensile strength perpendicular to the surface at various points throughout the panel thickness (tensile strength profiles) and correlated the observed values with the actual density at that point. The plots of vertical density and

tensile strength versus specimen thickness possess remarkably similar shapes (figs. 1 and 2). Plath and Schnitzler (1974) also present vertical density gradient diagrams for three particleboards--an air-felted board, a three-layer board, and a three-layer board subjected to prepress--and a medium-density fiberboard. Dramatic differences were noted between the air-felted particleboard and the three-layer particleboard not subjected to prepressing. The air-felted particleboard exhibited a symmetrical "U"-shaped gradient, but the three-layer board had a very thin region of high density approximately 2 mm below each surface. The three-layer board subjected to precompression possessed a vertical density distribution very similar to the air-felted

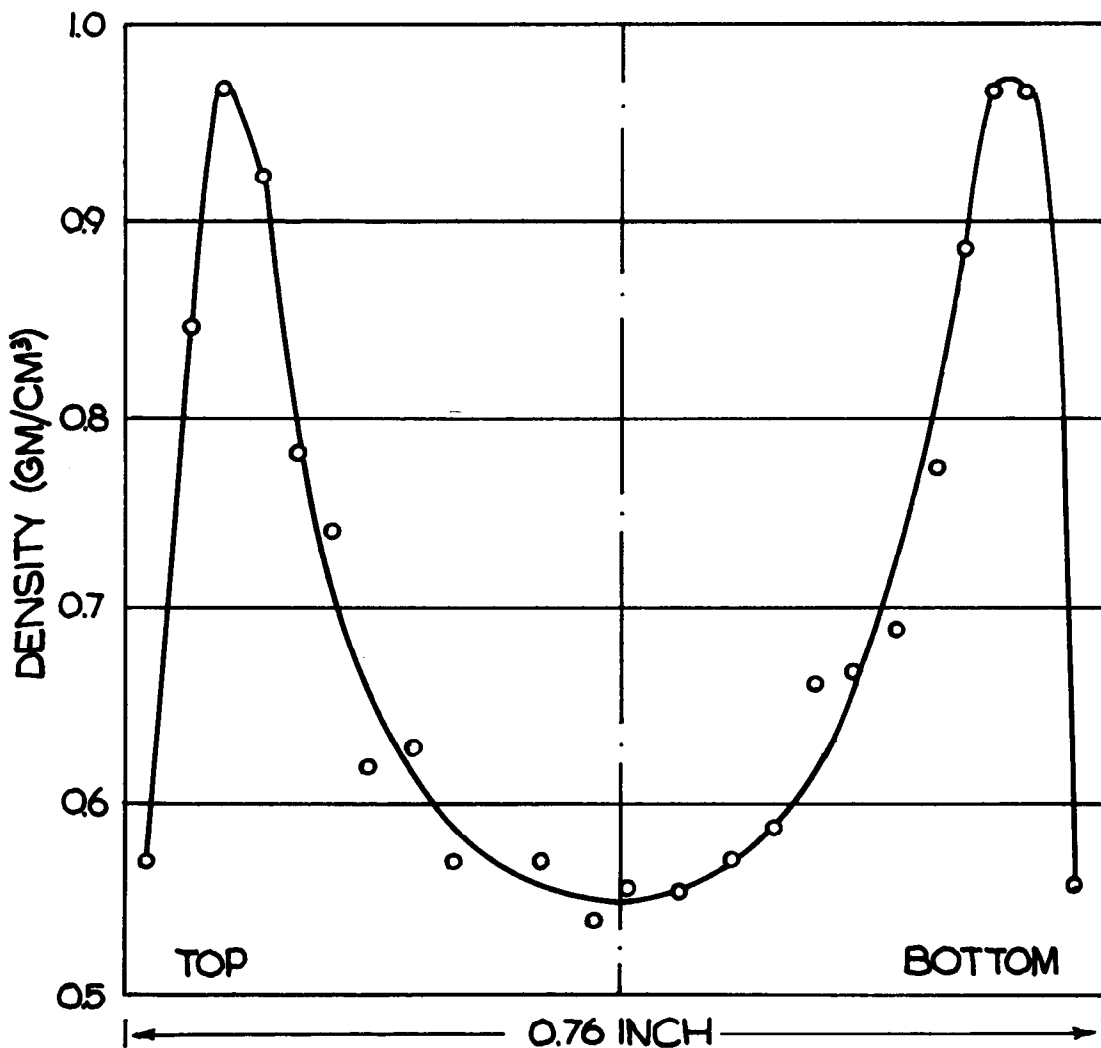


Figure 1.--Vertical density gradient of a three-layer particleboard.

(From Plath and Schnitzler 1974)

(M 144 401)

board except the bottom surface had a lower density. The medium-density fiberboard had a vertical density gradient similar to the air-felted particleboard, except the upper surface was lower in density. Consequently, the vertical density gradient of the medium-density fiberboard and three-layer precompressed particleboard would be expected to exhibit unbalanced dimensional changes with relative humidity changes because of the unsymmetri-

cal nature of the respective vertical density gradients.

The influence of mat moisture content and distribution, average board density, face weight of three-layer boards, press closure rate, and press cycle on the vertical density gradients in particleboard have been well documented by Strickler (1959), Heebink *et al.* (1972), and Geimer *et al.* (1975). Unfortunately, neither Strickler nor Geimer *et al.* shows the

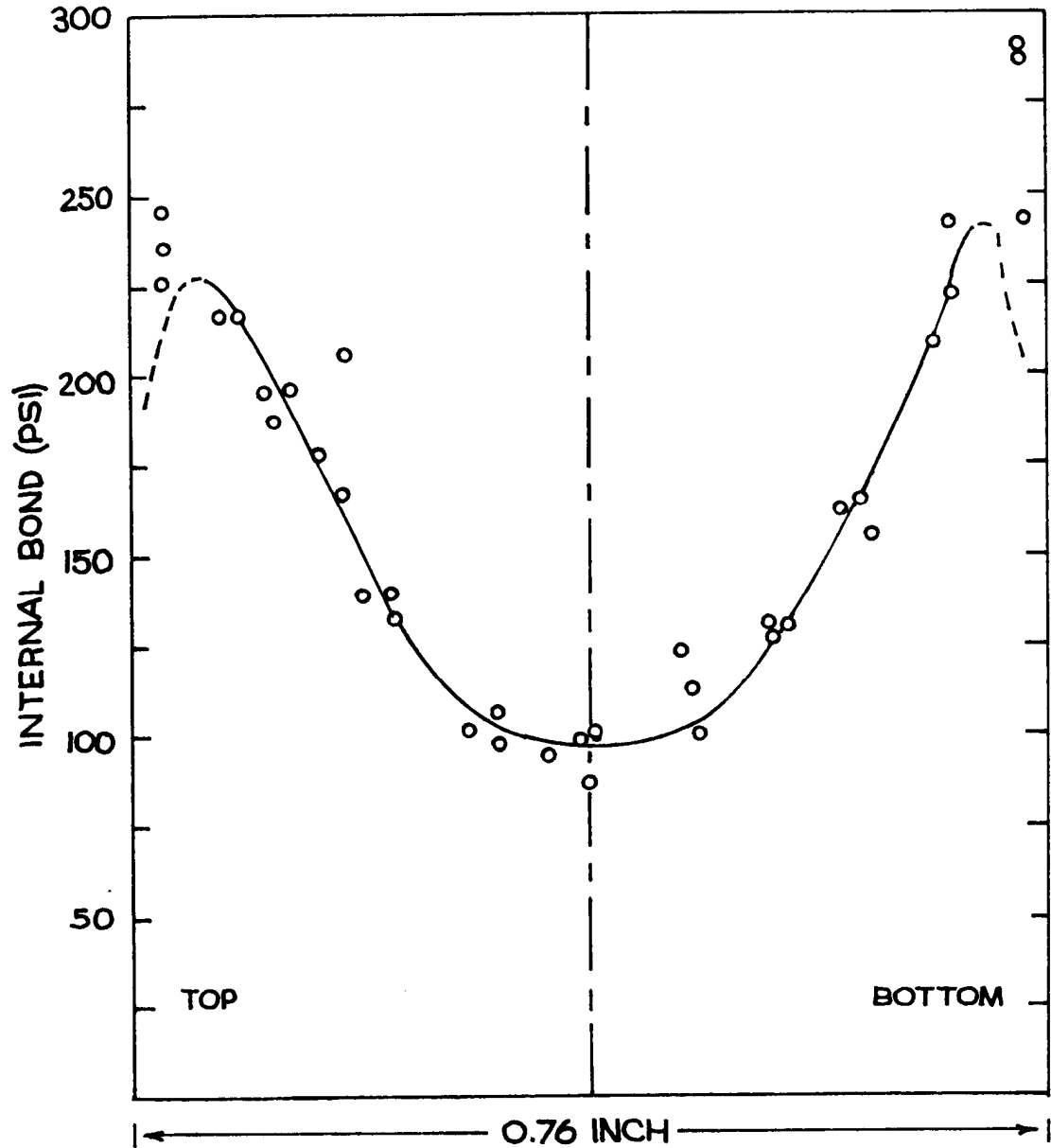


Figure 2.--Internal bond variation with thickness for a three-layer particleboard.

(From Plath and Schnitzler 1974)

(M 144 402)

vertical density throughout the entire thickness so the presence of unsymmetrical gradients remains undetected. However, the existence and influence of this vertical density gradient have been recognized by these authors.

The normal method of determining vertical density gradients is to accurately determine the weight and thickness of a given specimen, remove a thin layer from one surface, and accurately determine the weight and thickness of the resultant specimen. The density of the removed layer can then be determined from the weight and volume of material removed. This is normally referred to as the gravimetric method. This is repeated on both surfaces until the complete density profile is determined or on only one surface if only half of the density profile is desired (Strickler 1959; Heebink *et al.* 1972; Geimer *et al.* 1975). Unfortunately, there appears to be a general lack of concern as to the moisture distribution in the panels used for the vertical density gradient determinations. Because the gravimetric method used to measure the density gradient is not independent of moisture, variations in the moisture distribution in the thickness direction will be reflected in the density gradient. Consequently, the moisture gradient should also be determined on matched specimens when the vertical density gradient is determined by the gravimetric method. No measurements of moisture distribution were reported by Strickler (1959), Heebink *et al.* (1972), Plath and Schnitzler (1974), or Geimer *et al.* (1975).

An x-ray absorption method for measuring the vertical density gradient appears in the literature (Henkel 1969; Polge and Lutz 1969). The influence of a moisture gradient on this method is not discussed in either paper.

The vertical density gradient in mat-formed hot-pressed particleboard arises from the influence of temperature and moisture on the compressive stress of wood perpendicular to the grain (Suchsland 1962). The elevated press temperatures used to quickly polymerize the adhesives in the particleboard drastically reduce the compressive strength of wood. In addition, the mat normally enters the press at 8 to 15 percent moisture content. The combined effect of moisture and heat severely reduces the compressive strength of wood. However, the vertical density gradient does not result from high temperature and moisture content, but is due to the unequal distribution of moisture and heat as a result of the pressing operation. If the moisture and heat are equally distributed throughout the mat and remain

equally distributed throughout the entire pressing cycle, the stress-strain relationship for all particles of a homogeneous particleboard would be equal and no vertical density gradient would result (Suchsland 1962). This is obviously not the case with heated platen presses used in particleboard manufacture; consequently, hot-pressed particleboard possesses a vertical density gradient.

A closer look at the pressing operation is in order to more fully understand the underlying causes of the vertical density gradient. Strickler (1959) and Suchsland (1962) have each published excellent explanations of the phenomena present in a particleboard mat during consolidation in a heated platen press. An uncompressed mat placed in a hot press is compressed to the desired thickness over a finite period of time, depending upon the speed of press closure, final thickness, and the compressive strength of the component wood particles. Homogeneous particleboards, pressed at various closure speeds to a constant final thickness determined by the stops, will possess different vertical density gradients because of the time-dependent nature of the heat and moisture transfer through the mat and their resultant effect on the compressive strength of the various particle layers (Suchsland 1962). The time required to close the press to stops is directly related to the initial pressure; hence, a high initial pressure will cause the mat to reach final thickness before sufficient heat is transferred from the platens to the mat interior. Because the surface layers are hot, and therefore have lower compressive strength than the interior layers, compression of the wood structure in the surface layers will occur before compressive failure occurs in the interior. If the press closes to stops before the compressive strength of the interior layers is exceeded, all of the compressive failure will have occurred near the surfaces resulting in high-density face regions and a much lower density core, hence a sharp vertical density gradient. With a lower initial pressure, press closure speed will be slower, thereby allowing the interior to attain a higher temperature and a lower compressive strength before the stops are reached. The surfaces and interior will be more equal in density and the slower the press closure speed, the lower will be the vertical density gradient (Suchsland 1962).

Using the press closure time to control the vertical density gradient has some very obvious limitations. The adhesives used in particleboard production are temperature sensitive--*i.e.*, polymerization to a cross-linked polymer occurs rapidly at elevated temperatures. Con-

sequently, long press closure times will cause the adhesive on the particles in contact with the bottom hot platen to polymerize before sufficient interparticle contact has occurred. As a result, the bonding between surface particles will be drastically reduced and a very poor surface will be formed. This condition is referred to as a "precured" surface; the bending strength of "precured" particleboard is severely reduced. Another difficulty encountered in attempting to use press closure rate to limit the vertical density gradient is the lengthy press cycle which results. The capacity of properly designed particleboard plants is limited by the press cycle; increasing the press closure time will have an immediate and adverse effect upon the production level. Consequently, most processing changes which increase the press cycle are to be avoided.

In addition to closure rate, another method, which has been frequently studied and is widely used by the industry to control the vertical density gradient, is the "steam shock" treatment (Fahrni 1956; Strickler 1959; Deppe and Ernst 1965; Heebink *et al.* 1972; Geimer *et al.* 1975). This technique uses steam to quickly heat the mat interior to more nearly equalize the rate of reduction in compressive strength through the mat thickness. Also, because the compressive strength of wood is inversely related to the moisture content, the additional moisture will further reduce the compressive strength, allowing mat compression to occur at a lower pressure.

It would be helpful to review the work of Maku *et al.* (1959) and Strickler (1959) to determine the rate of heat transfer from the hot platens to the mat as well as to determine the effect of this unsteady state heating process on moisture distribution and movement across the mat thickness. It is the rate at which moisture and heat migrate into the mat during the press closing period that determines where compressive failure will occur to allow consolidation of the mat to the desired thickness. Once the stops have been reached, very little additional compressive failure occurs; consequently, the density gradient is established during press closing.

Maku *et al.* (1959) studied the moisture and temperature distribution in homogeneous particleboard mats composed of two different particle configurations, with moisture contents of 1, 11, 14, 22 and 30 percent, when subjected to pressure in a hot press. Thermocouples located at various points through the mat thickness allowed them to monitor the temperature at each location as it varied with press time, at a press temperature of 135° C.

Because no adhesive was used, moisture content samples at various thickness locations were also obtained to determine the moisture content distribution as a function of time. The press times used by Maku *et al.* for 3/4-inch-thick particleboard were unrealistically long (up to 60 minutes). However, this allowed them to monitor the mat temperature and moisture content for extended time periods.

The core temperature as a function of press time was distinctly different for the two particle types (figs. 3 and 4). The particle configuration referred to as granular was 0.2 to 0.4 inch long, 0.04 to 0.2 inch wide, and 0.004 to 0.08 inch thick and consisted of an unspecified mixture of birch and beech species. The flake particles were practically square thin particles entirely of birch; the range in particle dimensions was reported as 0.3 to 0.6 inch long, 0.1 to 0.8 inch wide, and 0.004 to 0.02 inch thick. For all mats with granular-type particles, with the exception of the mat at 1 percent moisture content, the core temperature increased rapidly to 100° C and remained constant at this temperature for various time periods depending on the initial mat moisture content. However, in the mats with the flake-type particles and high initial mat moisture contents, the core temperature reached a maximum above 100° C in the early stages of pressing, decreased slowly to 100° C, remained at this temperature for some period of time, and then increased smoothly toward the platen temperature at extended press times. The maximum temperature reached by the mat core in the early stages of pressing was a function of furnish moisture content; furnish at a 30 percent moisture content resulted in a higher core temperature than furnish at 20 percent moisture content.

Strickler (1959) reported the maximum initial temperature rise in the core of mats with uniform moisture contents of 6, 9, and 12 percent to be inversely proportional to moisture content. The moisture content range studied by Strickler includes the range in which Maku *et al.* (1959) did not observe a core temperature maximum. Strickler (1959) states: "...1) the maximum temperature achieved (core) by the initial rise was governed by moisture content and was controlled thereafter by moisture content, and; 2) the temperature tended to dip after the initial-rise maximum." Because the particle size used by Strickler (0.5 inch long, 0.375 inch wide, and 0.008 inch thick) was very similar to the flake-type particles of Maku *et al.* (1959), and because the press temperatures and specific gravities were comparable, the reported differences in the core temperature at similar

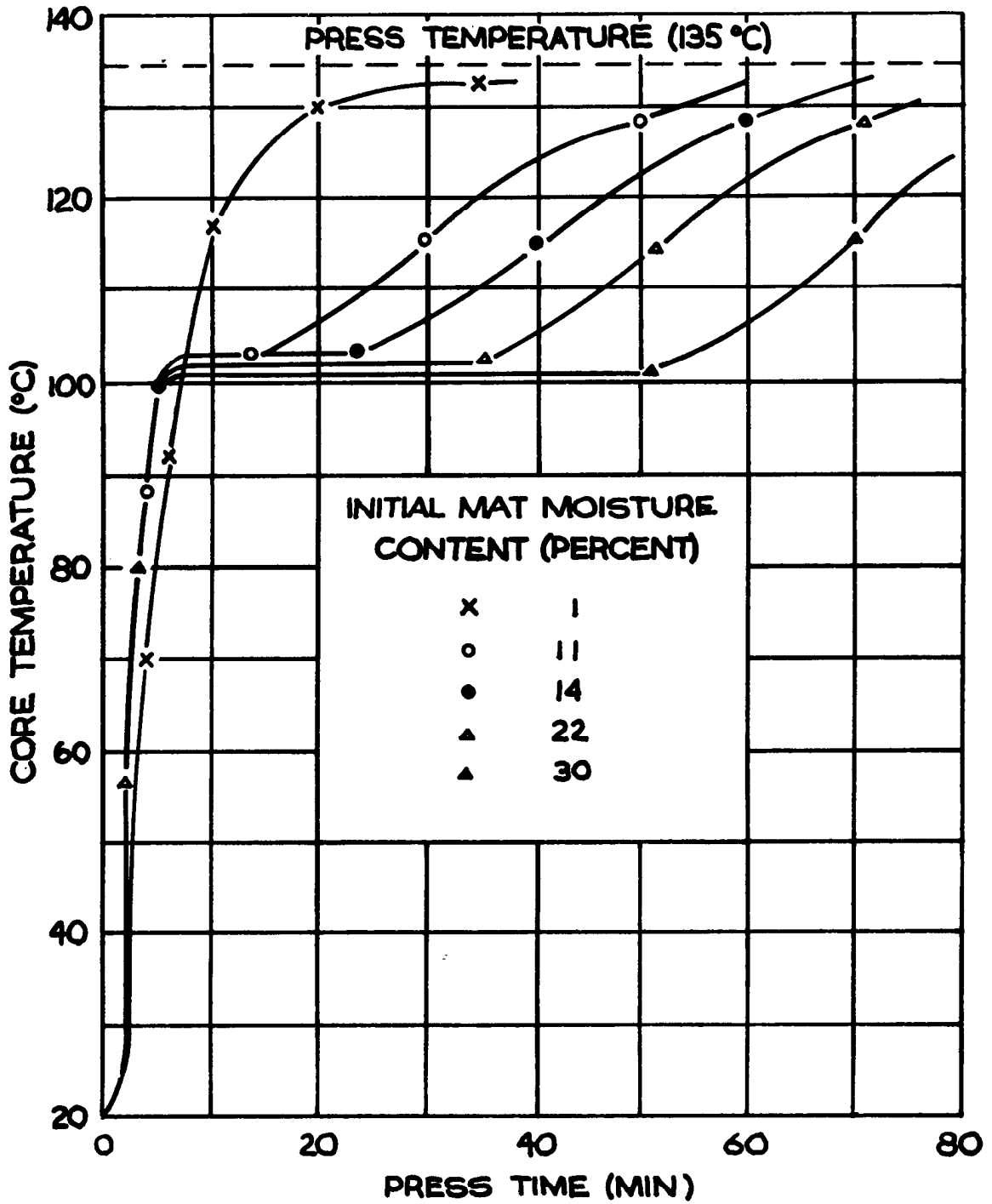


Figure 3.--Influence of initial moisture content and press time on the core temperature with the granular-type particle mat (SG 0.65).
(From Maku et al. 1959)

(M 144 403)

moisture contents must be the result of some other unrecognized and undetermined variable. Strickler (1959) did report higher initial

maximum core temperatures as the surface moisture contents increased from 12 to 30 percent.

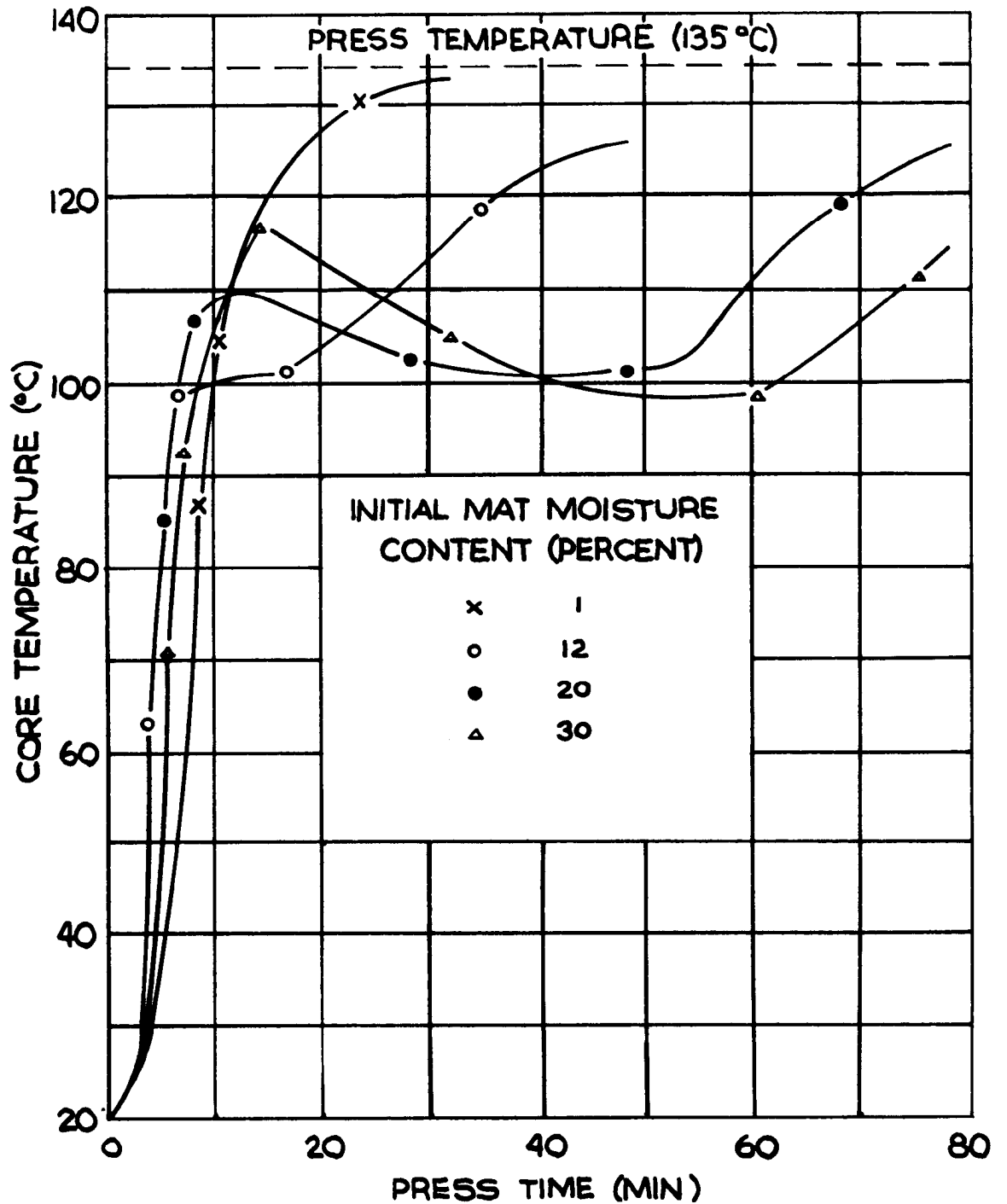


Figure 4. --Influence of initial moisture content and press time on the core temperature with the flake-type particle mat (SG 0.75).
 (From Maku et al. 1959)
 (M 144 404)

Maku et al. (1959) also presented data illustrating the effect of mat moisture distribution on the core temperature with three mats of granular-type particles. All mats had the

same average moisture content of 23 percent but different initial distributions -- i.e.: a uniform distribution of 23 percent moisture content; inner three-fourths at 10 percent and the

surfaces at 58 percent moisture content; and the inner half at 10 percent and the surfaces at 35 percent moisture content. No initial maximum in the core temperature was reported; all mats exhibited a plateau at 100° C. The core temperature of the three-layered construction with 58 percent surface moisture content increased above 100° C in the shortest time; the core temperature of the mat with a uniform moisture content of 23 percent remained at 100° for a substantially longer time,

Maku *et al.* (1959) found the maximum initial core temperature to be a function of the board specific gravity for the flake-type, but not the granular-type, particles at a moisture content of 25 percent. Strickler (1959) found no relationship between the board specific gravity and the maximum initial core temperature at moisture contents of 6, 9, and 12 percent. However, both Strickler and Maku *et al.* found it took longer to reach the maximum core temperature as the specific gravity increased, although the increased time was not proportional to the additional mass.

Maku *et al.* (1959) determined the core temperature rise for three-layer particleboard with different ratios of surface to core particles consisting of flake- and granular-type, respectively. The moisture content was constant (25 percent) for all mats. The results are consistent with homogeneous boards: As the relative amount of flake-type material increased, the initial core temperature increase above 100° C was higher, the subsequent decrease to 100° C was more obvious, and the time period until the core temperature finally increased above 100° C was longer.

Strickler (1959) did not measure moisture distribution in the mat as a function of press time, as did Maku *et al.* (1959)(fig.5). Maku *et al.* found the moisture distribution to be symmetrical around the board centerline and, for a homogeneous board with the granular-type particle at 21 percent initial moisture content, a reverse moisture gradient evident at a 5-minute pressing period indicated moisture had migrated from the surface towards the core but the core was still at the initial moisture content. The moisture distribution in a homogeneous board with the flake-type particle did not possess this reverse moisture gradient. Unfortunately, the data do not allow a direct determination of the relationship between particle geometry and moisture movement in the mat since the particleboards produced with each particle were of different specific gravities--flake-type, 0.65 and granular-type, 0.8 (conditions at which specific gravity determined unknown). However, the conclusion

drawn by Maku *et al.* (1959) that vertical moisture movement is very slight with the flake-type particle (as compared with substantial vertical moisture movement in the granular-type particle) appears to be valid. For both of the above homogeneous particleboards, a moisture content gradient still existed after 45 minutes in the hot press at 135° C.

The three-layer board, with the flake-type particle surface representing 2/7 of the total thickness and an initial moisture content of 43 percent, and the core with the granular-type particle at an initial moisture content of 7 percent, had the expected reverse moisture gradient at 3 minutes pressing time. The moisture content at 1/4 thickness was approximately 18 percent, while the surfaces and core both were at approximately 10 percent. At a pressing time of 10 minutes no reverse gradient was evident; the core moisture content was 10 percent. After 35 minutes in the press the gradient was entirely lacking.

Unfortunately, Maku *et al.* (1959) did not produce bonded particleboard; their objective was to follow the temperature and moisture behavior in a mat with no interference from the adhesive. Consequently, they could not determine vertical density gradients. The results of portions of their study are in good agreement with many of Strickler's (1959) results and, because Strickler did determine vertical density gradients, it is possible to use these two papers to review the effect of moisture and temperature on the vertical density gradients in hot-pressed mat-formed particleboard. However, there are also areas in which differences exist in the results of the respective papers and the lack of experimental detail in Maku *et al.* prevents resolution of these differences.

Strickler (1959) showed that high initial pressure (rapid press closing) resulted in a high surface density and a low center density. This results from the short time period for heat and moisture transfer into the mat; consequently, compressive failure occurs only in the wood of the surface layers, not in the core layer.

Heat transfer to the center of a particle mat in a hot press is strongly influenced by moisture content (Maku *et al.* 1959; Strickler 1959). Strickler pointed out that two moisture gradients exist in a particle mat: one of increasing moisture content from the hot platens to the mat center and another of decreasing moisture content from the middle area of the mat to the edges, along the centerline plane. Moisture at the mat surface vaporizes when the press closes and the resultant steam flows to a cooler

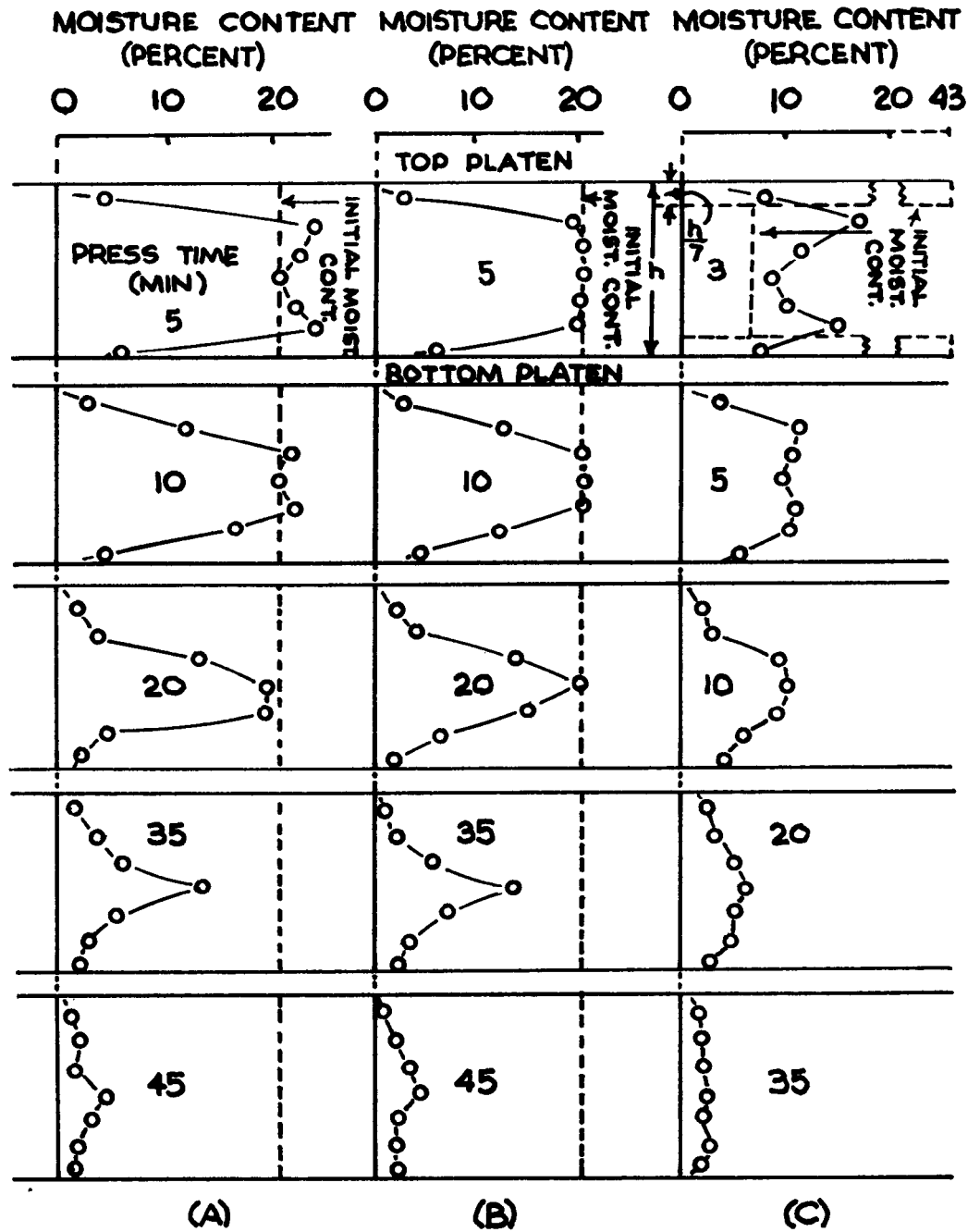


Figure 5.--Moisture distribution in particle mats as influenced by press time. (A) Granular-type particle, SG 0.8, initial mat moisture content 21 percent. (B) Flake-type particle, SG 0.65, initial mat moisture content 21 percent. (C) SG 0.65, initial mat moisture content, core 7 percent (granular type), face 43 percent (flake type).
 (From Maku et al. 1959) (M 144 405)

region (toward the mat center) where it condenses. Consequently, the moisture content of the intermediate and core layers should increase in the early portion of the press cycle. This was reported by Maku et al. (1959). How-

ever, the steam resulting from vaporization of the surface moisture will transfer heat to the mat core much more quickly than if transfer were entirely by conduction (Strickler 1959). Consequently, increasing the surface mois-

ture content will speed the temperature increase of the core.

Strickler (1959) and Maku *et al.* (1959) both reported data indicating that the initial temperature rise in the core for mats of flake-type particles produced a temperature exceeding the boiling point of water. The core temperature after this initial maximum decreased to near the boiling point of water as the press time increased. Strickler also showed that for moisture contents below 12 percent the maximum temperature rise in the core decreases as the moisture content increases. He attributed this to higher vapor pressures which force the moisture to flow along the centerline to the mat edges and escape more rapidly. However, vapor pressures are a function of temperature, not water content; more water may be evaporating from the mat edges to the atmosphere in a given time period at the higher moisture content, and evaporative cooling may keep the core temperature lower. Maku *et al.* (1959) in contrast to Strickler did not find a maximum core temperature for the flake-type particles at 12 percent moisture content. Particle geometry cannot account for the different results obtained by Maku *et al.* (1959) and by Strickler (1959) as particle configuration was similar in both studies. The contrasting results must arise from other unrecognizable sources.

Particle configuration and its relationship to moisture migration from the mat central areas to the edges along the core may account for the core temperature differences between mats of flake-type and mats of granular-type particles noted by Maku *et al.* (1959). The initial core temperature of mats with granular-type particles did not rise above 100° C for any moisture content conditions tested: 1, 11, 14, 22, and 30 percent. If the porosity of the mat with this particle was sufficiently high to allow rapid venting of the center moisture directly to the edges, the core temperature should not exceed the boiling point of water until the free water in the core has evaporated. Also, the time period during which the core will remain at constant temperature, assuring constant heat flow to the center, should be directly proportional to the quantity of water evaporated to the atmosphere. The data (Maku *et al.* 1959) show the core temperature to increase above 100° C at a press time of 14, 23, 35, and 51 minutes for a moisture content of 11, 14, 22, and 30 percent respectively. Figure 6 (from Maku *et al.* 1959) shows the linear relationship between the initial mat moisture content and the time in the press before the core temperature rises above 100° C. This appears to illustrate that free water is present in the core of the mat with the granular-type particle and its rate of re-

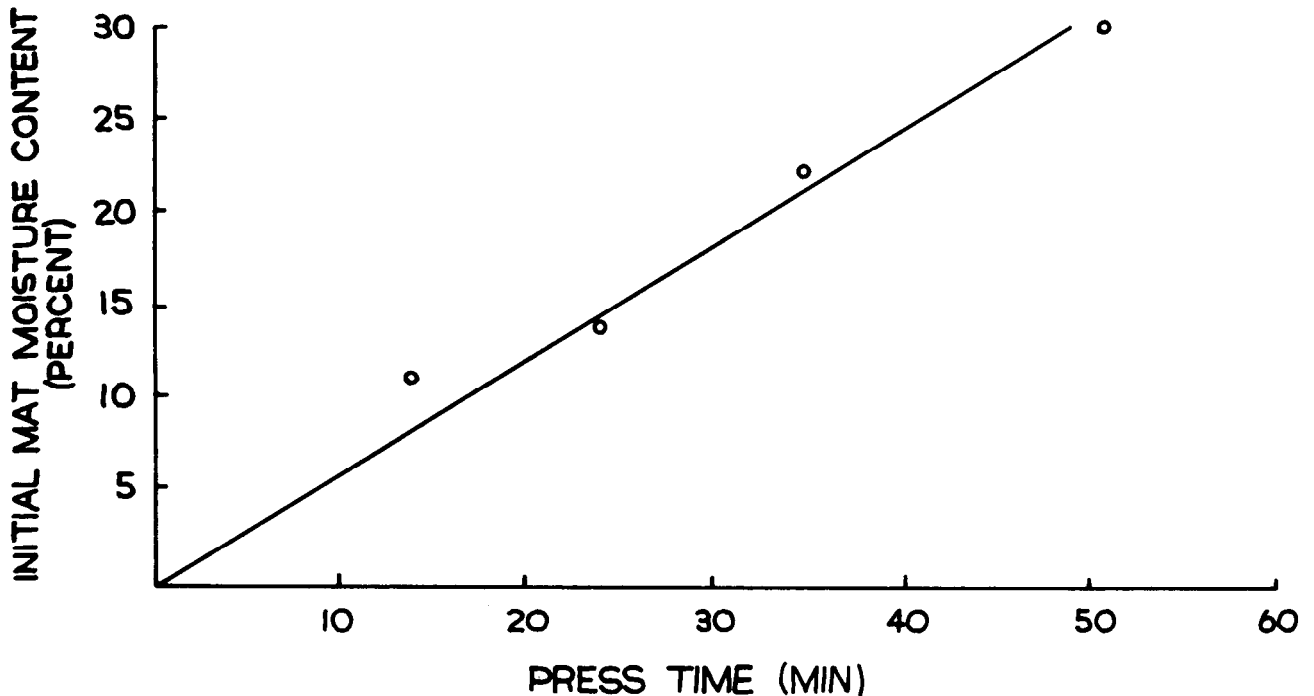


Figure 6.--Relationship between initial moisture content and the press time at which the core temperature rises above 100° C for the granular-type particle. (Adapted from Maku *et al.* 1959)

(M 144 406)

moval is controlled by heat flow to the center. The flake-type mats in which the core temperature rose above 100° C do not have this linear relationship between initial mat moisture content and the time of final core temperature rise above 100° C.

From the above it appears either that the granular-type particles allow faster water movement along the center to the mat edges than do the flake-type particles, or that the flake-type particles allow more rapid heat movement from the mat surfaces to the core. However, because the rate of the initial temperature rise of the core appears to be approximately the same for the two particle types at equal moisture contents, the increased porosity of the granular-type particle mat appears to be indicated. This particle type is probably stiffer than the flake-type and does not compress and mat together as well as the flakes.

The mats with flake-type particles at high (20 and 50 percent) moisture contents exhibited a peak in the core temperature above 100° C (Maku *et al.* 1959). This indicates heat transfer to the core from the faces is faster than heat transfer to the mat edges for this particle type. However, because most of the heat is transferred by steam, data indicate that, in the early stages of pressing, moisture movement from the faces to the core is quicker than from the core to the edges, resulting in a superheated interior. Unfortunately, the moisture content gradients presented by Maku *et al.* cannot be used to compare the moisture distribution as a function of press time for the two particle configurations as mats of unequal specific gravity are shown.

The dip in the core temperature after the initial temperature rise, observed by both Maku *et al.* (1959) and Strickler (1959), indicates a net loss of heat in this region. This is most likely due to a net loss of moisture in the core; more heat is being consumed to evaporate water to the atmosphere through the centerline than is being released by condensation of water migrating to the core from the mat surfaces. The moisture gradients of Maku *et al.* do show a decreasing core moisture content at a press time approximately equal to the temperature dip. Strickler also pressed a mat without adhesive to verify that the exothermic heat of condensation of the resin was not responsible for the core temperature rise and subsequent dip.

The effect of moisture content on vertical density gradient was shown by Strickler (1959) to result in more severe gradients as the moisture content increased. Because stops were

not used for thickness control, it is impossible to correlate the results directly to a process using stops; however, the data do illustrate that moisture content, initial pressures, and specific gravity are all positively correlated to the magnitude of the vertical density gradient. Strickler also showed that a high surface moisture content increased the density of the surface and intermediate layers while decreasing the center density. Therefore, moisture distribution as well as moisture content has a substantial effect on the vertical density gradient. Thus, the "steam shock" surface treatment introduced by Fahrni (1959) serves to magnify density variations in the thickness direction of particleboard.

Heebink *et al.* (1972), as part of a larger study, examined the effect of various processing factors on density and vertical density gradients in particleboard. Variables studied were species, particle geometry, board density, board thickness, moisture content and distribution, and press time, temperature, and closing speed. Moisture content and distribution within the mat were the most important variables affecting the vertical density gradient. Press closing speed and press temperature also contributed to the vertical density gradient; all other variables had secondary effects. Strength properties were also highly dependent upon the vertical density gradient.

Only at extremely rapid closure speeds (15 seconds) did the maximum density result at the surface. With longer closing times, the vertical density distribution was lower at the surface, rising rapidly to a maximum within 3/32 inch from the surface and then decreasing to a lower density core (Heebink *et al.* 1972). A very sharp vertical density gradient was obtained with a high surface moisture content (15 percent) and low core moisture content (5 percent); however, with the core at 15 percent and the surface at 5 percent, a relatively flat gradient with the maximum density at the core was obtained (fig. 7). Unfortunately, moisture content gradients in the particleboard as it came from the press were not determined, only the average moisture content of the board. The results obtained by Heebink *et al.* (1972) on the effect of initial mat moisture distribution on the vertical density gradient agree with those of Strickler (1959). As the closing time increased (Heebink *et al.* 1972), the vertical density gradient was reduced--i.e., the density of the maximum-density region decreased and the core density increased.

Geimer *et al.* (1975) determined the vertical density gradients on three-layer Douglas-fir structural particleboards with two surface-

to-core ratios and three press closing speeds. Surface flakes were 2 by 0.5 by 0.02 inch in length, width, and thickness, respectively. The large surface flakes retard moisture movement to the core so a larger portion of the compressive failure occurs in the surface resulting in higher surface densities. Therefore, not only press closure speed, but also different amounts of surface material for a given thickness will contribute to the vertical density profile. Geimer *et al.* also showed that, depending upon the vertical density gradient obtained with a given press closure, the average surface density can be increased or decreased with an increase in the surface material.

Included also in Geimer's report (1975) was the effect of particleboard thickness, at a constant density, on the vertical density gradient. At a constant average density, increased thickness resulted in an increase in the face specific gravity at both face-core levels studied. Therefore, thicker boards will have steeper vertical density gradients at constant average density and closure speeds because

heat and moisture will not reduce the compressive strength in the interior quickly enough to allow the compressive failure to be more equally distributed across a larger portion of the total thickness.

Maloney (1970) included density profile measurements, as part of a larger study on resin distribution in three-layered and multi-layered particleboards. The particleboards with high resin faces had surface specific gravities approximately 11 percent higher than boards produced under the same experimental conditions but with lower surface resin contents. The average initial mat moisture content was given as approximately 10 percent in both cases, but the higher resin content surface also must have had a higher moisture content since the solids content of the adhesive was not adjusted. Therefore, the density profile differences reported as due to resin content could instead have been the result of moisture differences.

The development of the vertical density gradient within the hot press appears to be

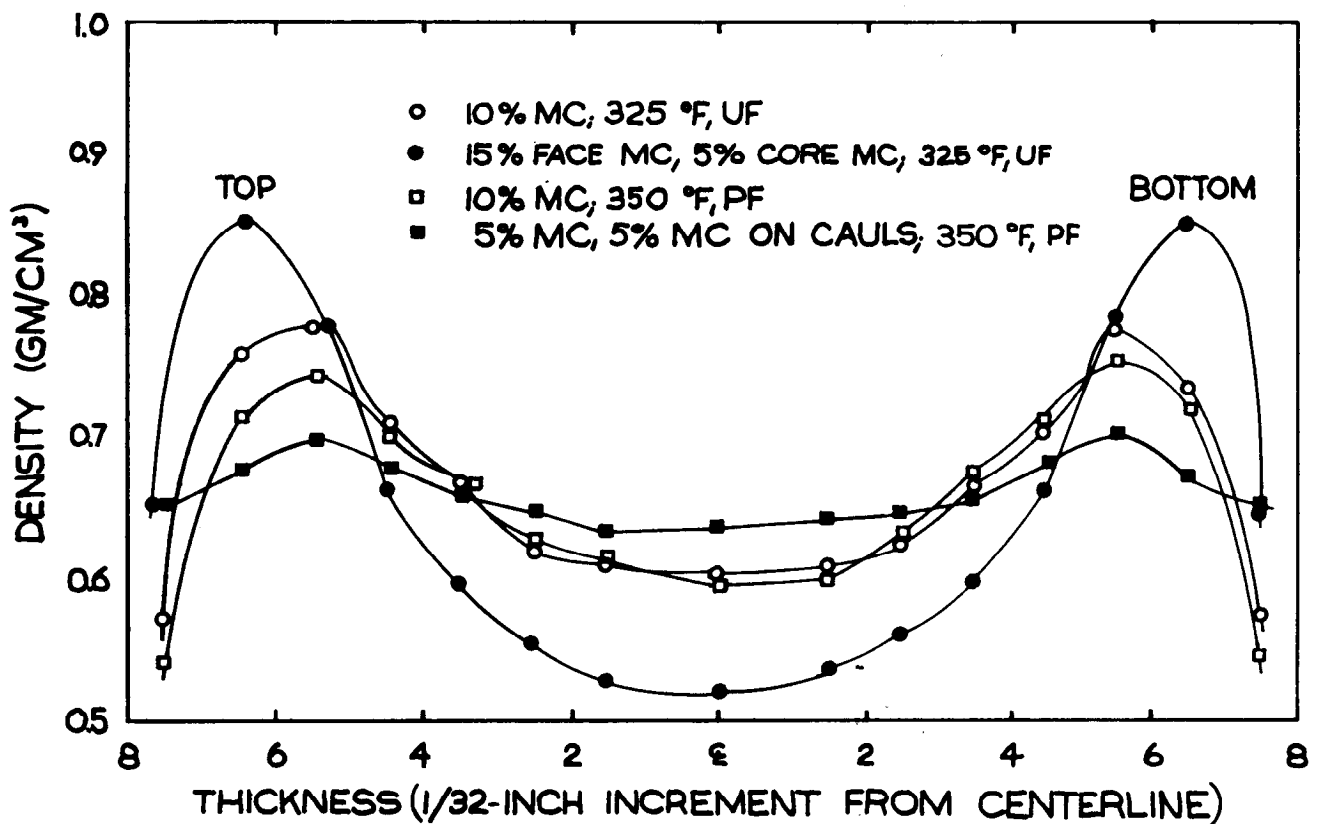


Figure 7.--Effect of various moisture and temperature conditions on vertical density gradients in 0.5-inch particleboard.

(From Heebink *et al.* 1972)

(M 144 407)

fairly well documented although not all parameters contributing to its development have been fully studied. However, the lack of information relative to its influence in the major portion of the particleboard literature is distressing and it is hoped that determining the vertical density gradients will become much more widely practiced by researchers in the near future. Many observed particleboard properties attributed to various processing parameters may be the result of unmeasured differences in the vertical density gradients.

Formaldehyde Release

The release of formaldehyde fumes from particleboard bonded with urea-formaldehyde resins is a problem which has been frequently studied. The human nose is extremely sensitive to formaldehyde; formaldehyde detection is possible at 0.8 ppm (Walker 1964). The rate of formaldehyde release from particleboard decreases with time from the press; temperature and humidity during storage, shipping, and usage also influence the rate of release. Processing conditions, such as time in the press, moisture content, adhesive content and reactivity, and press temperature all influence the rate of formaldehyde release. The difficulty encountered in attempting to study factors affecting formaldehyde release is the lack of a quantitative analytical procedure for the low concentrations of formaldehyde normally encountered and correlation of the test results to formaldehyde released from the particleboard in use. The procedures used to study formaldehyde release from particleboard are many and varied. This discussion will be on the results obtained by investigators using various procedures in studying the effect of processing variables on formaldehyde release from urea-formaldehyde bonded particleboard. The release of formaldehyde from phenol-formaldehyde-bonded boards is not a problem, due to the irreversibility of this polymer.

Neusser and Zentner (1968) have presented a general description of the problems encountered with urea-formaldehyde-bonded particleboard. They believe it is necessary to apply an impermeable coating to particleboard if large amounts of the board are to be used in an enclosed environment.

Wittmann (1962) has pointed out the necessity of free, or unreacted, formaldehyde in urea-formaldehyde resins to allow the condensation reaction to occur. Most of this formaldehyde is consumed in the curing reaction in particleboard manufacture, but a portion remains in the voids and will gradually escape.

Even heating the board under vacuum to remove the free formaldehyde in the voids will not produce an odor-free particle board (Wittmann 1962). Formaldehyde is also released at the press during manufacture (Petersen *et al.* 1972), but this formaldehyde is of less concern to the end-user than is the formaldehyde released from the cured resin. Residual formaldehyde is normally considered to be the formaldehyde loosely bound in the finished particleboard, which tends to split off the polymer structure after the manufacturing process is completed.

Wittmann (1962) studied the residual formaldehyde released from particleboards produced with various resin contents, press time, and catalyst contents, stored at various conditions. Increasing the resin content from 6 to 12 percent (resin solids on oven-dry weight of wood) did not significantly increase the residual formaldehyde. Particleboards produced with increased press times, at constant ammonium chloride levels, had decreased residual formaldehyde. Increasing the ammonium chloride content at constant press times also decreased the residual formaldehyde. Wittmann also found reduced levels of residual formaldehyde in particleboards containing increasing amounts of ammonium hydroxide as well as increasing amounts of urea. Petersen *et al.* (1974) found formaldehyde levels reduced with ammonium salts but not with the heavy metal salts such as magnesium chloride or aluminum sulfate. Deppe and Ernst (1965) reported that formaldehyde release was lowered with increasing levels of ammonium chloride. Ginzel (1973) also found a lower residual formaldehyde level in particleboards with resins containing ammonium salts and urea. Plath (1968) attributed the reduced residual formaldehyde found with ammonium salts to the reaction between the ammonium group and formaldehyde which results in hexamethylenetetramine. Wittmann (1962) pointed out that addition of ammonia and urea, while helping to alleviate the residual formaldehyde release, would result in slow resin cure and detrimental strength and hygroscopic properties, respectively.

Plath (1966; 1967a; 1967b; 1967c; 1968) using a calorimetric method specifically for formaldehyde, studied the effect of press time and temperature, ammonia level, and mat moisture content on residual formaldehyde released from laboratory-produced particleboard. He found a decrease in residual formaldehyde as the press temperature increased (125, 135, 145, and 155° C) and as the press time increased (3, 6, 9, and 12 minutes). In-

creased press temperature was more effective than increased press time in reducing the residual formaldehyde (Plath 1967a). Data also indicated that the rate of resin cure was inversely related to the residual formaldehyde. At higher press temperatures the adhesive in the surface regions should cure more quickly than at lower temperatures, but the curing rate of the core will be much less increased by the higher temperatures because of the water migrating to the core. Hence, increasing press temperature will increase the curing rate of the resin at the surfaces more than the resin in the core and, since the residual formaldehyde from the surface was reduced more than that from the core with increasing press temperature, it was concluded that rate of cure was a substantial influence on residual formaldehyde. The quantity of formaldehyde released from the core was always greater than from the surface. The degree of cure, as well as the rate of cure, was also inversely related to the residual formaldehyde release as indicated by less residual formaldehyde at longer press times.

Addition of ammonium-containing hardeners to the urea-formaldehyde resin also reduced the residual formaldehyde (Plath 1967b). Hardeners with 10 to 30 percent ammonium reduced the formaldehyde to a level comparable to that obtained by increasing the press time from 3 to 12 minutes. However, the strength and hygroscopic properties were also reduced at the high ammonium levels. Increasing mat moisture content increased the residual formaldehyde (Plath 1967c); the increase was greater at the surface than at the core.

Plath (1968) also found an increased residual formaldehyde content when the panels were hot-stacked out of the press. Hot-stacking also resulted in a higher residual formaldehyde release from the surface than present immediately out of the press. Plath (1968) attributed this to the migration of the moisture with dissolved formaldehyde from the core to the surface during equalization, although an equally valid reason would be migration of formaldehyde from the highly concentrated core region to the surface which initially has a lower formaldehyde concentration.

Petersen *et al.* (1972) measured the formaldehyde released during hot pressing of a mat at 16 percent moisture content and found it to be 50 percent greater than from a mat at 10 percent moisture content. The formaldehyde/urea molar (F/U) ratio also had a significant effect on formaldehyde released during pressing. A resin with an F/U ratio of 1.8/1.0,

with a particle mat at 10 percent moisture content, released 2.5 times more formaldehyde than did a resin with an F/U ratio of 1.4/1.0. Petersen *et al.* showed that increasing the solid resin content did not proportionally increase the formaldehyde liberated during pressing. Also, increasing the mat moisture content increased the formaldehyde released during pressing more at the 5 percent resin solids level than occurred at 12 percent resin solids. More total formaldehyde was released during pressing as press time and temperature increased. The board which released the most formaldehyde in the press did not release as much residual formaldehyde after storage, but the decrease in residual formaldehyde was not as great as the increase in formaldehyde released during pressing. For example, with a F/U molar ratio of 1.8/1.0 and a press temperature of 160° C, an 8-minute press cycle released, during pressing, approximately twice the formaldehyde of the 5-minute press cycle. However, after storage, the residual formaldehyde determined on the 8-minute board was only slightly less than the residual formaldehyde in the board pressed for 5 minutes. Therefore, the total formaldehyde released was greater for the board with the longer press cycle.

Formaldehyde liberated during the pressing cycle for three particle species was also determined by Petersen *et al.* (1973). Oak liberated the most formaldehyde, spruce the least, and beech was midway between. This is the only information found in which formaldehyde was released by mats of different species has been determined.

Deppe and Ernst (1965) indicated the formaldehyde released at the press was reduced as the amount of moisture evaporated per unit surface area of the mat increased--i.e., as the mat moisture content increased, the formaldehyde at the press decreased. Plath (1967c) found that residual formaldehyde released from finished particleboards increased as the mat moisture content entering the press increased. The lower formaldehyde at the press reported by Deppe and Ernst (1965) could have been the result of a lower degree of reaction; hence the formaldehyde would weakly bond through ether linkages in the press and would subsequently be released as residual formaldehyde (Plath 1967c). If this is in fact the case, a compromise in mat moisture content is then required to insure that the formaldehyde fumes in the press area and the residual formaldehyde released from the board are both at acceptable levels.

Christensen (1972) found moisture con-

tent, temperature, and resin composition to have the greatest effect on formaldehyde liberation. He studied the residual formaldehyde in particleboards by heating the panel under vacuum and adsorbing the evolved formaldehyde in water. The results were comparable to those of earlier investigators in that formaldehyde emission increased with board moisture content and decreased with increasing press time. With the two resin content levels used by Christensen (1972), the formaldehyde emission increased approximately linearly with the resin content increase. This is contra-

dictory to the results of Petersen *et al.* (1973) in which formaldehyde release did not increase in proportion to the increased resin content.

Christensen (1972) also presented a plot in which the logarithm of formaldehyde release was linearly related to the particleboard temperature (fig. 8). A plot of formaldehyde emission versus board moisture content was linear at moisture contents below 9 percent; above 9 percent the formaldehyde emission continued to increase, but at a decreasing rate (fig. 9). The concentration of formaldehyde released at 70° C was the same as that released

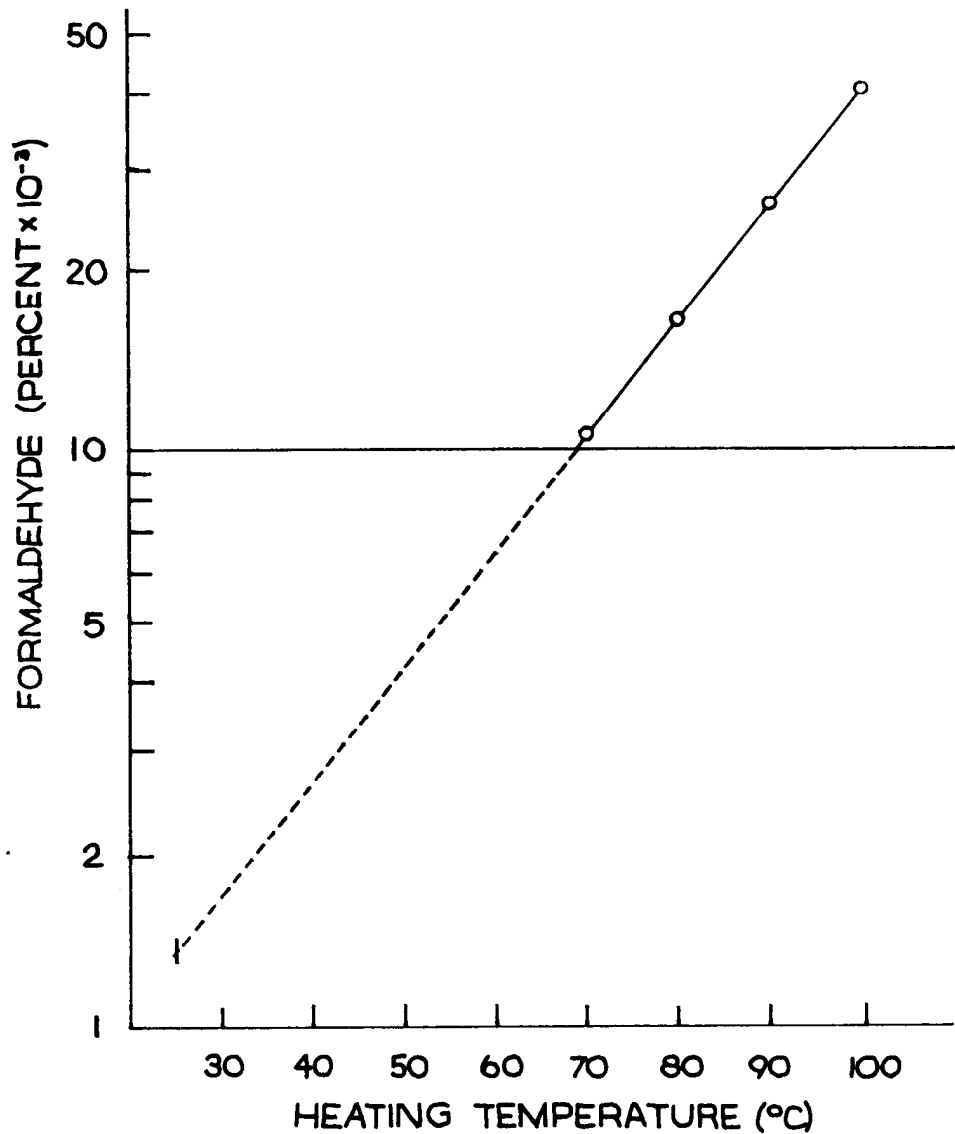


Figure 8.--Influence of heating temperature on residual formaldehyde
(From Christensen 1972)
(M 144 408)

at 3 percent moisture content. Therefore, in normal interior applications for particleboard it would appear that the moisture content is more important than the temperature in controlling formaldehyde release.

Many factors appear to influence formaldehyde release from particleboard; no single

processing parameter appears to be controlling this phenomenon. Resin changes which will potentially reduce formaldehyde liberation will also lengthen the press cycle, result in resin precure, or have adverse effects upon the product's strength properties. Manufacturing compromises are required and are normally

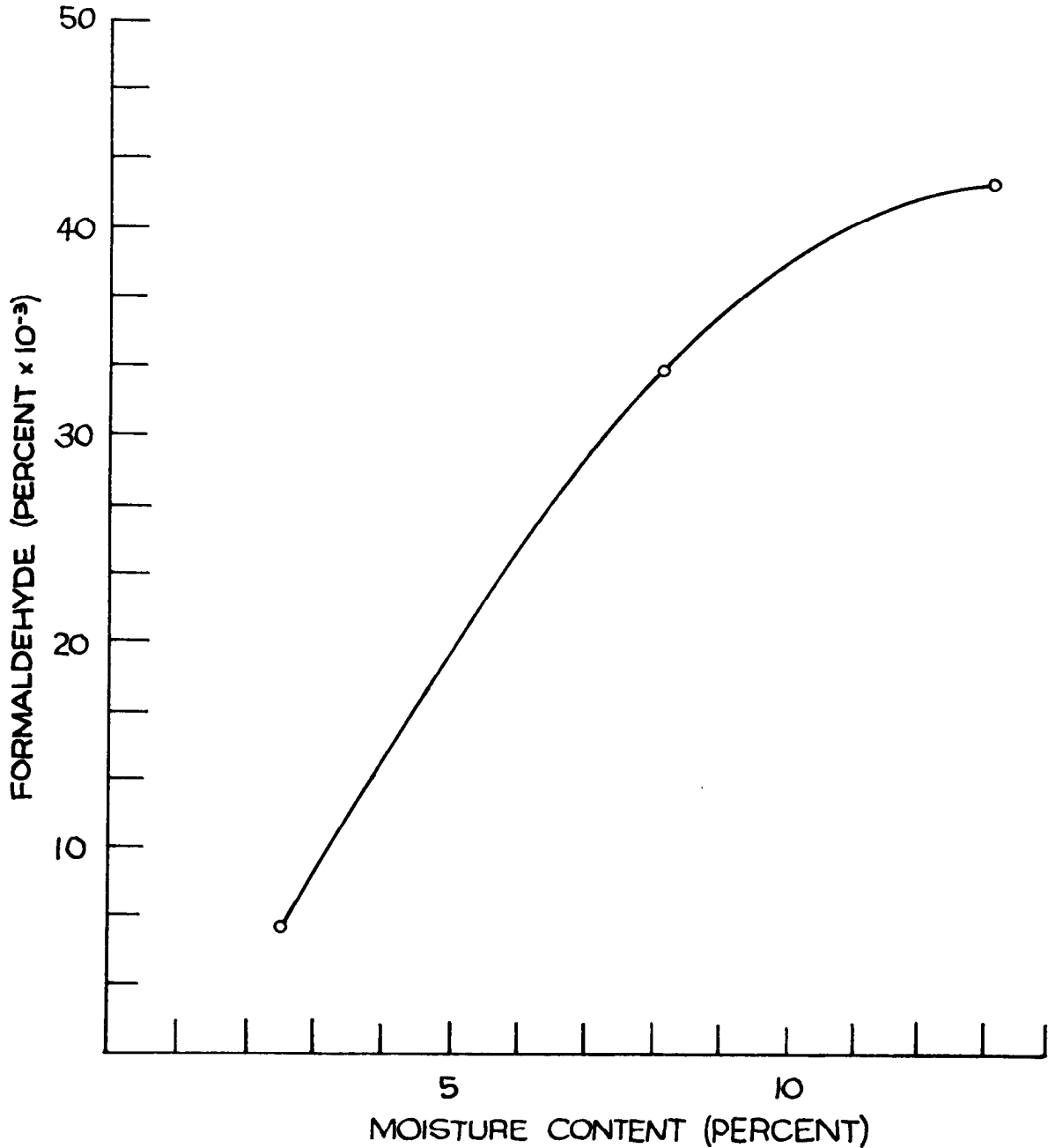


Figure 9.--Influence of particleboard moisture content on residual formaldehyde.

(From Christensen 1972)

(M 144 409)

made on subjective instead of objective factors due to lack of a reproducible, meaningful, quick analytical procedure for measuring formaldehyde release from both a particleboard panel and a mat in the press.

Springback

Springback is the nonrecoverable thickness swelling that occurs when a finished particleboard, in equilibrium with a given temperature and humidity, is exposed to an elevated humidity, or liquid water, and subsequently returned to the original humidity and temperature condition. Particleboard is much more dimensionally unstable in the thickness direction than would be expected from the normal shrinking and swelling of the component wood particles.

The additional thickness swelling in particleboard exposed to moisture, greater than that normally expected for wood material, is due to the release of residual compressive stresses imparted to the board during the pressing of the mat in the hot press. As shown earlier, compressive failure of at least a portion of the wood particles is required to produce particleboard. The moisture content reduction while the mat is restrained in the hot press reduces the plasticity of the wood and results in a semipermanent "set" of these compressive stresses. However, at any future date when the moisture content increases, the additional moisture will plasticize the wood and allow these stresses to be relieved, allowing expansion in the thickness direction. The particleboard will also swell due to adsorption of water by the hygroscopic particles of wood. The total thickness swelling for particleboard exposed to moisture is the sum of these two components. Subsequent redrying will result in thickness shrinkage equal only to the shrinkage of the particles; none of the compressive stress release will be recovered (Neusser *et al.* 1965; Beech 1975). Additional wetting and drying cycles will also result in further irrecoverable thickness swelling, but at a decreasing rate.

Because most of the literature reviewed in the moisture and dimensional properties section does not differentiate between hygroscopic swelling and compressive stress relief, the literature pertaining to springback studies will be reviewed here.

Childs (1965) studied the effect of chip width, resin content, and board density on the springback of urea-formaldehyde-bonded particleboards made from sweetgum chips. As expected, springback increased with increasing board density and decreased with increasing resin content. As the board density

increases, more compressive failure is imparted to the particles which will springback on rewetting and, as the resin content in creases, the component particles are stabilized so springback will be reduced. Springback characteristics were independent of chip width.

Saito (1972) studied the springback of both commercial and laboratory particleboards soaked in water to constant thickness and subsequently oven-dried. Phenolic bonded boards were more stable than boards with urea-formaldehyde resins; melamine-formaldehyde bonded particleboards were close to the phenolics. Water temperature during soaking had no effect on springback, but the temperature used for preliminary drying was directly related to the amount of springback, because higher temperatures plasticized the wood to a greater degree.

Beech (1975), using a phenol-formaldehyde resin, reported a significant lowering of springback when the phenolic adhesive level was increased from 9 to 12 percent. This was attributed to increased bonding between the particles. The portion of the irreversible thickness swell associated with glue failure was found to be slight as compared to thickness swell as a result of stress release. Beech also reported that post-treatment with saturate steam at 160° C was effective in reducing both irreversible and reversible thickness swelling. Apparently the high temperature steam changed the hygroscopicity of the wood and allowed stress release to occur.

Turner (1954) reported springback in phenolic-bonded particleboards to be governed by resin content and panel density. However, his definition of springback includes thickness swelling as well as true springback since the reported values are the percent thickness increase after exposure to two water soak-drying cycles. This study examined the properties of homogeneous panels produced with various particle configurations; all particle types with 4 percent resin yielded boards with less thickness swelling after two exposure cycles than seven-ply Sitka spruce plywood. This is one of the rare instances where particleboard has been reported to have lower thickness swelling than plywood; the high specific gravity (0.80, at unspecified moisture content of the particleboard) could account for this result.

Post (1961) reported that springback increased as flake thickness increased in urea-formaldehyde-bonded particleboard. This effect was evident with all flake lengths although an interrelationship between flake

length and thickness was apparent (fig. 10). Four-inch-long flakes resulted in significantly lower springback at greater thicknesses.

Springback is a characteristic property of flat-pressed particleboard and is present in all boards. Adjustments in processing parameters can be used to reduce the springback tendency, but due to the nature of the product it cannot be eliminated. Whenever particleboard is subjected to conditions which increase the

plasticity of the wood (high moisture, or both high temperature and high moisture) the thickness swelling will exceed that predicted by moisture absorption alone.

There have been various attempts to reduce dimensional changes in the thickness direction of particleboard by reducing the hygroscopicity of the particles or reducing the compressive set in the final panel. These attempts have been reviewed by Halligan

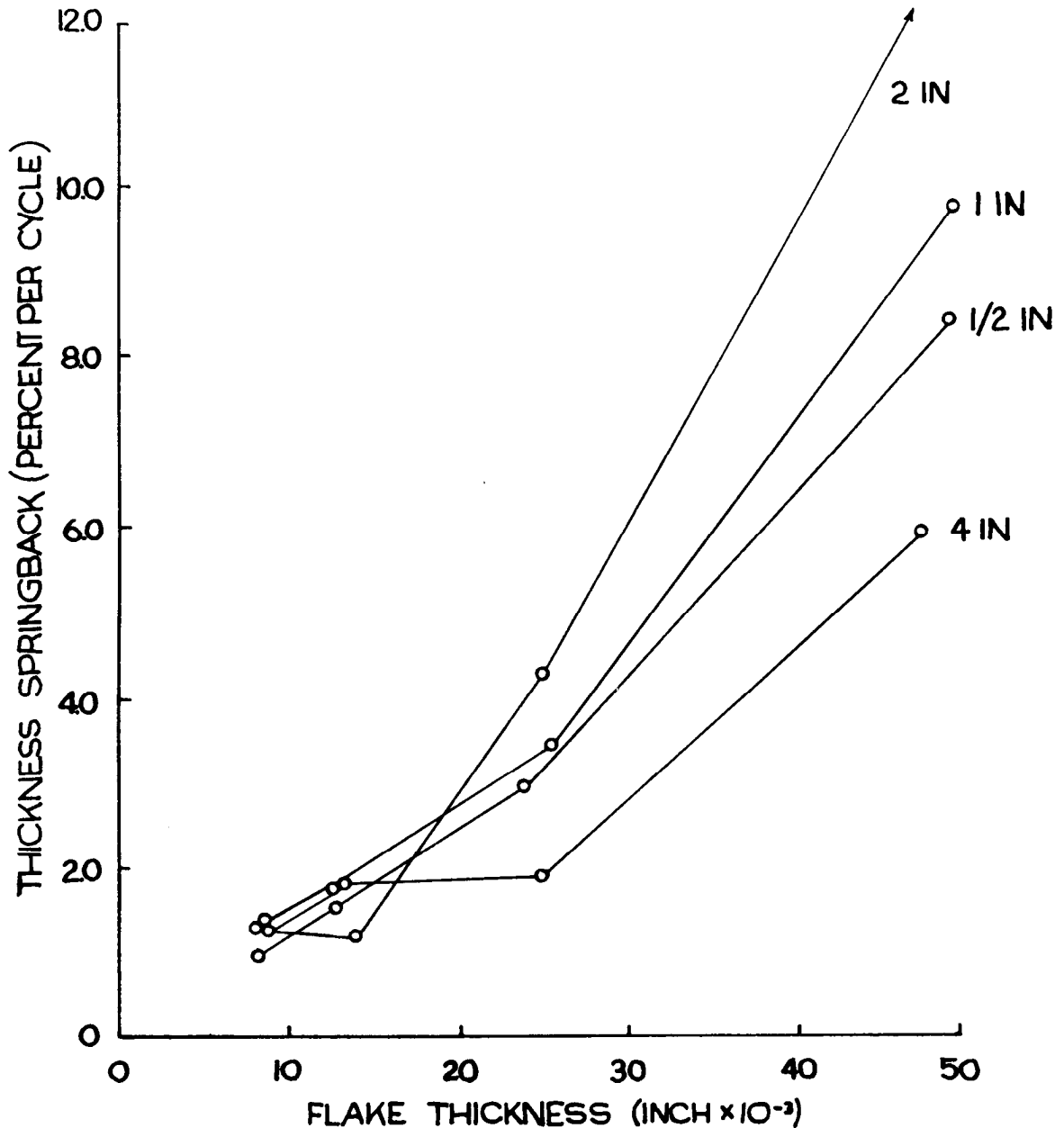


Figure 10.-- Thickness springback as influenced by flake dimensions.
(From Post 1961)

(M 144 410)

(1970) and do not presently appear to be commercially feasible. Steam and/or heat treatment of the cured particleboard appears to effectively reduce springback in phenolic-bonded material (Heebink and Hefty 1969; Halligan and Schniewind 1972; Shen 1973; and Beech 1975). Heebink and Hefty reported that a 10-minute treatment with saturated steam at 360° F was the most effective post-treatment to reduce springback. Post-treatment without thickness restraint under the above conditions had no effect on the linear stability and only a slight reduction in bending strength. Because springback is the result of compressive failures in the hot press, pretreatment methods to be only one-half as effective in reducing springback as the most post-treatment on the final particleboard.

Halligan and Schniewind (1972) found a direct linear relationship between the springback and thickness swelling for urea-formaldehyde-bonded particleboards exposed to various relative humidities. The close relationship between springback and thickness swelling led Halligan and Schniewind to conclude there was no need to consider the two properties separately. However, because their data are based on only the first adsorption cycle after pressing, it would be expected that subsequent sorption cycles would result in much less springback and hence a different relationship between the two properties.

Halligan and Schniewind (1972) also post-treated phenolic-bonded particleboard with steam and found springback eliminated below 90 percent relative humidity and reduced to less than one-third of untreated boards at relative humidities above 90 percent. Post-treatment of urea-formaldehyde particleboards with steam is not feasible due to the degradation of the resin under heat and moisture conditions.

Shen (1973), in an attempt to produce phenolic-bonded particleboard with lower springback and without steam post-treatment, adapted a hot press to allow direct injection of steam from the press platens into the mat. The steamcured particleboards had improved dimensional stability but came out of the press at 10 to 15 percent moisture content instead of the normal 2 to 5 percent. The potential advantage of this method is that the resin is cured in a steam atmosphere which allows relaxation of a large portion of the compressive stresses induced in the particles during pressing. However, this method does not appear feasible due to the high moisture content of the produced board and the difficulty inherent in attempting to force the

steam through the mat.

Suchsland and Enlow (1968) used a 2-hour heat treatment at 425° F to allow relaxation of the compressive stresses in phenolic-bonded particleboard. Boards subjected to this treatment exhibited better surface smoothness, less thickness swelling and more strength retention at high humidities than did untreated boards. This severe treatment resulted in a slight reduction in the modulus of elasticity, which was attributed to thermal deterioration of the wood components.

Mikhailov and Ostapenko (1972) attributed the springback of particleboard to a nonuniform moisture content distribution in the thickness direction. They recommended lengthening the press time and reducing the mat moisture content to alleviate this tendency. This practice should reduce the moisture gradient from surface to core in the final panel, but the moisture gradient normally would be expected to contribute in only a minor way to particleboard springback.

Neusser (1967) and Deppe and Ernst (1965) have used the term springback to characterize the thickness increase of particleboard immediately out of the press. This is not the same phenomenon referred to here as springback; this expansion occurs for most particleboard upon pressure release in the hot press. Neusser (1967) used this initial expansion as a measure of the curing rate of various adhesives; the more completely the resin cured in the press the less was this immediate expansion. Deppe and Ernst (1965) found this initial expansion to be a problem with very short press times at moisture contents above 10 percent. This initial or immediate expansion is no problem in properly produced particleboard where the resin is sufficiently cured.

Springback resulting from residual compressive stress release appears to be most effectively controlled by a steam post-treatment. As a result of the production process for particleboard, compressive stresses are incorporated which, upon subsequent exposure to higher moisture, result in excessive thickness swell and subsequent application difficulties. Allowing the release of these residual compressive stresses by steaming results in a more dimensionally stable product for all applications. Most studies concerned with thickness swelling of particleboard, as will be shown in that section, combine the thickness resulting from moisture adsorption with the springback from stress release. Therefore, the thickness swelling reported is only accurate for the initial moisture content increase; all subsequent moisture content cycles should have a

lower percentage thickness swelling, but the total thickness will continue to increase (Liiri 1961).

Surface Characteristics

The particleboard literature is surprisingly deficient in studies concerned with processing parameters and their effect upon the surface smoothness. Obviously, roughness in the platens or cauls used to press the particleboard will be reflected on the board surfaces, but this cause of roughness is easily eliminated. Other surface smoothness influences--moisture content, particle type, and other controllable process parameters--are touched on in the literature reviewed here.

Plath (1971a) has reviewed the requirements for particleboards laminated with plastic overlays and has concluded it is impossible to develop criteria applicable for all laminating applications. In addition to a smooth and uniform surface, moisture and density distributions, chip characteristics, and bending strength are also important.

The lack of a simple and objective test procedure to quantify surface properties remains a problem (Hunt 1965; Gatchell *et al.* 1966; Kehr 1966; Neusser, Krames, Haidinger, and Serentschy 1969; Neusser, Krames, and Zentner 1969; Kehr and Jensen 1970; Neusser and Krames 1971). Optical methods with reflected light are normally used. Gatchell *et al.* used the shadow projected by two parallel wires as a semiquantitative measure for surface roughness; the sharpness of the shadows and the variability of the distance between the two shadows were related to surface smoothness.

Kehr (1966), Kehr and Jensen (1969), and Neusser, Krames, and Zentner (1969) all reported improved surface characteristics as the particle size decreased. Kehr and Jensen point out that strength properties are reduced and dimensional changes increased with decreasing particle size. Neusser, Krames, and Zentner also mention this and further point out the difficulty in blending and mat forming with fibrous surface particles, although this configuration does not adversely affect the strength. They further report that soft to semi-soft, diffuse-porous hardwoods are more suit-

able for surfaces than pine which splinters.

Kehr (1966) also reported improved surface characteristics obtained with addition of wax. This is possibly due to the inhibiting effect of the wax on absorption of liquid water which reduces the ensuing swelling. Hunt (1965) studied the effect of moisture on show-through of veneered particleboard and found the show-through reversible with moisture content. Show-through at high moisture contents disappeared at lower moisture contents. Also, compressed softwood particles moved 3 to 8 times as much as uncompressed wood of the same species upon exposure to relative humidity changes. Undoubtedly, this additional movement was due to the springback mentioned earlier.

Neusser, Krames, Haidinger, and Serentschy (1969) have shown the importance of chip configuration on various particleboard properties. Surface stability is a function of thickness, planarity, and swelling characteristics of the chip, and surface porosity is a function of the chip thickness, density, and compressibility.

Shen (1974) reported an improvement in surface smoothness by repressing particleboard at 500 to 650° F under 250 to 600 pounds per square inch (lb/in.²) for a few seconds. This treatment plasticized the surface and resulted in a smooth, nonabsorbent, and hardened face. The treated surface was improved with no detrimental effects, and reportedly bonded satisfactorily with commercial urea-formaldehyde laminating resins. Longer times at high temperature and pressure resulted in some deterioration of the surface.

The increased application of particleboard in direct surface finishing will result in increased emphasis on surface quality. Quantitative methods of assessing surface quality have to be developed and more emphasis placed on techniques for producing a uniform surface during manufacture. The various methods used in the above literature illustrate the need for standard test methods; each investigator has developed his own test and comparisons between his criteria for acceptable surfaces and those of another investigator are impossible.

PROCESSING PARAMETERS

Resin efficiency, adhesive type and level, furnish, and pressing conditions are the processing parameters examined here for their effects on particleboard properties,

Resin Efficiency

Resin costs are a major portion of the total manufacturing expense of particleboard. Consequently, optimum board properties with

minimum adhesive consumption is the goal of all manufacturers; this concept is referred to as resin efficiency. Continuous, cured glue-lines are not obtained between individual particles because the resin is normally sprayed on the particles in discrete individual droplets. Not all particles are in intimate contact with neighboring particles over their entire surface after mat consolidation in the press. Adhesive deposited on surfaces adjacent to interparticle voids will not contribute at all to bonding. Therefore, minimizing the interparticle voids--increasing board density--will normally improve the board properties at constant resin content.

Resin efficiency in particleboard is difficult to study directly due to the problems encountered in quantitatively measuring the amount of liquid adhesive sprayed on the surface of irregularly shaped particles. The amount of resin solids normally used in particleboard manufacture is only a fraction of that used for plywood and other solid wood gluing. Meinecke and Klauditz (1962) have discussed the theoretical glue-line thickness obtained if the entire particle surface is coated with a resin solution of 50 percent total solids. Even with a chip 0.03 inch thick sprayed with 50 percent resin solution to 8 percent solids on a dry wood basis, the resulting film of water and resin would be only 25 μm thick (Meinecke and Klauditz 1962).

The adhesive is normally applied to the component particles by spraying fine droplets of the resin solution on continuously agitated chips. This agitation allows some rubbing action between adjacent chips to further disperse the adhesive. Resin efficiency, as measured by improved physical and strength properties, increases as the droplet size from the spray nozzle decreases and the degree of dispersion of the adhesive solution increases (Carroll and McVey 1962; Meinecke and Klauditz 1962; Kehr *et al.* 1964; Lehmann 1970; Christensen and Robitschek 1974). Therefore, the finer the adhesive spray, the better is the possibility of maximizing the fraction of particle surface covered.

In addition to a well-dispersed spray, increasing the rubbing action between individual particles as they are agitated in the blender enhances the possibility for resin transfer from one particle with excessive adhesive to another particle deficient in adhesive. Christensen and Robitschek (1974) reported higher internal bond values for particleboards produced from furnish exposed to extended post-blending agitation as compared to boards from furnish without the post-blending.

They also showed, by mixing two screened fractions of chips with and without urea-formaldehyde adhesive, that interparticle resin transfer occurred during agitation. Subsequent screening and nitrogen determination on the initially resin-free fraction showed that resin transfer to this fraction from the other fraction had occurred in the blender. Kehr *et al.* (1968) also showed that resin transfer from neighboring particles in the blender contributed to improved particleboard properties.

Carroll and McVey (1962) in a similar study found only slightly improved properties with extended mixing time. They sprayed the required adhesive on only 50 percent of the furnish, added the remaining furnish, and mixed the total in a rotating drum blender for 30 minutes. The internal bond and modulus of rupture properties for the resultant particle board were less than 5 percent higher than those in which the post-blending of the two fractions was only 5 minutes. This illustrates the relatively limited value of trying to improve the resin distribution by prolonged post-mixing; much better results can be obtained by optimizing the original blending.

Meinecke and Klauditz (1962) reported a drop in tensile strength both perpendicular and parallel to the surface as the resin droplet size increased from 35 to 100 μm (fig. 11). Droplets smaller than 35 μm did not improve the tensile strengths. Because sections examined under the microscope showed only relatively few areas without adhesive, improvements in strength by further decreasing the droplet size would be expected to be small. Meinecke and Klauditz also stated that industrial blenders normally operate with a droplet diameter around 80 μm and, consequently, improved board properties could be obtained commercially by reducing droplet size. Carroll and McVey (1962) also reported lower internal bond and modulus of rupture values for industrial boards as compared to identical laboratory boards. This was attributed to poorer industrial blending; when laboratory-blended material was pressed in the industrial press, the particleboard was equal in strength to the laboratory board. The industrial blender did not blend the furnish and resin as well as the laboratory blender, possible due to the larger droplet size in the industrial blender (Meinecke and Klauditz 1962).

Carroll and McVey (1962) do not agree with Meinecke and Klauditz (1962) concerning the value of a continuous film on the particle surface. Carroll and McVey found extremely low internal bonds (30 to 40 $\text{lb}/\text{in.}^2$), even at 7 percent resin content (resin solids on OD wood), for a phenolic adhesive that flowed into

a continuous film. However, when they used a particleboard phenolic resin that did not have the high flow properties, excellent internal bonds were obtained (180 lb/in.²). They believed the thin film which resulted when the low resin content spread into a continuous film formed a starved glue joint. Carroll and McVey believed a large number of spot welds uniformly distributed throughout the mat would be superior to a continuous film.

Lehmann (1965) obtained optimum board properties at a given resin content when a uniform distribution of resin was applied by fine atomization. Modulus of rupture, modulus of elasticity, internal bond, and dimensional stabilization all improved when the droplet size of the urea-formaldehyde adhesive decreased. Burrows (1961), using a phenolic binder, found modulus of rupture to be independent of the atomization level. The atomization which produced the best internal bond was related to the adhesive content; fine atomization at 2 percent and coarse atomization at 6 percent adhesive content produced the highest internal bonds (Burrows 1961).

Spraying with adhesives of lower total solids has been shown to increase the resin efficiency in particleboard (Carroll and McVey 1962; Carroll 1963). This will result in less resin solids in each droplet on the particle surface but more droplets per unit of particle area.

This would appear to coincide with the theory of Meinecke and Klauditz (1962) and Marian (1958) that a continuous resin film is the optimum condition for particleboard production. A low level of water dilution significantly lowers resin viscosity but also increases the amount of water added to the furnish. The additional adhesive volume may lengthen the blending time or force the blenders to operate with an even larger droplet size (Carroll and McVey 1962; Meinecke and Klauditz 1962). Kehr *et al.* (1964) have shown the detrimental effect on properties with increasing "throughput per nozzle." As the "throughput per nozzle" increased, the blending time, dimensional stability, and strength properties of the particleboard all decreased. Lower "throughput per nozzle" resulted in a more uniform distribution, due to the smaller droplet size, and all properties subsequently improved.

Pecina (1963) measured the dimension and distribution of resin droplets on particle surfaces by adding fluorescent dye to the resin, photographing the particle under UV radiation, and determining the fraction of surface area covered with resin. His paper has no information comparing different blending techniques, only development of the test procedure.

Lehmann (1970) added a dye to a urea-formaldehyde adhesive and determined the

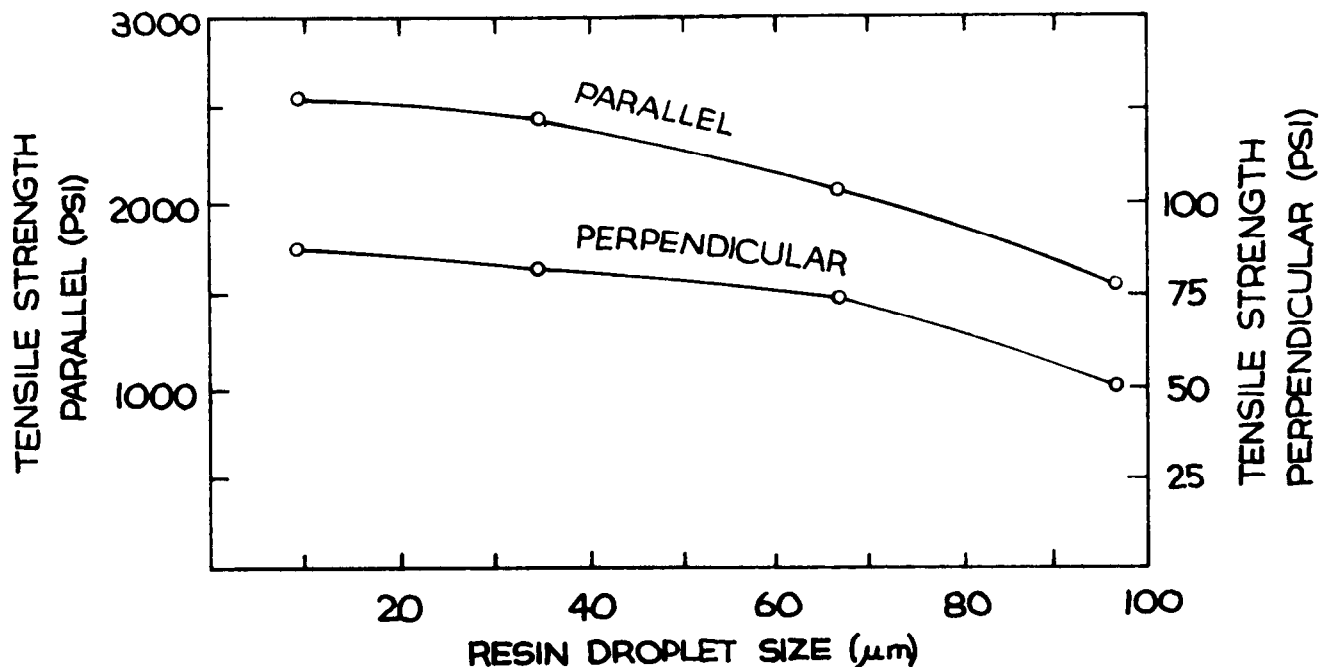


Figure 11.--Influence of resin droplet size on tensile strength perpendicular and parallel to particleboard surface.

(M 144 411)

relative area of resin coverage on particles with three different resin contents (2, 4, and 8 percent) and two atomization levels (fine and coarse) by measuring the reflection of the dyed resin. Fine atomization was found to result in better particle coverage at all resin contents and particle sizes. Resin efficiency also increased with board density but this was attributed to better bonding efficiency between particles, not to resin distribution.

Lehmann (1968) also added a fluorescent dye to urea-formaldehyde and phenol-formaldehyde adhesives to study the interparticle bonding in flakeboard. Two atomization levels were used and the location and distribution of the adhesive in the finished particleboard was determined by photomicrographs under ultraviolet (UV) light and correlated to the resultant physical properties. Resin applied as a fine spray always produced better properties than the same resin applied as a coarse spray. Photomicrographs revealed that continuous gluelines were produced with 6 percent urea-formaldehyde (resin solids on oven-dry wood--OD--wood) and almost continuous gluelines with only 4 percent of the phenol-formaldehyde (resin solids on OD wood) when both were applied as a fine spray. Lehmann (1968) also photographed boards made with diluted, low-viscosity urea-formaldehyde resin applied in a fine spray. No penetration of the resin into the particles was observed, and with the exception of the internal bond, the physical properties were not decreased. Lehmann (1968) also used a diluted, low-viscosity phenol-formaldehyde resin with an airless spray; results were the same as those obtained with the diluted urea-formaldehyde resin. This is contradictory to the results of Carroll and McVey (1962) with a high flow phenol-formaldehyde resin. Carroll (1963) also reported that resin efficiency for urea-formaldehyde adhesives is lost as a result of apparent migration of low-molecular-weight components into the wood substance.

Lehmann (1965) reported that airless spraying did not distribute the resin as well as the air sprayer; agitation of the particles was less without the excess air. There appeared to be no large significant differences in the board properties attributable to spraying method. Fine atomization of the resin improved strength and dimensional stability to a greater extent than did spraying method, spraying temperature, or solids content of the resin (Lehmann 1965). Best results were obtained by spraying at room temperature with a high resin solids content. This is contradictory to the findings of Carroll and McVey (1962) and

Carroll (1963), in which better resin efficiency was obtained by spraying diluted resins. However, the decrease in properties with decreasing solids content found by Lehmann (1965) was, in all cases, relatively small.

One additional problem encountered when applying resin to wood particles is the particle size distribution normally found in all samples of wood particles: Resin treatment levels in particleboard are normally based on resin solids as a percent of the oven-dry wood weight. However, the resin function in particleboard is to bond individual particles into a consolidated mat by establishing an adhesive bond between the surfaces of adjacent particles. As the particle size at a constant weight of oven-dry wood decreases, the total surface area increases. Therefore, to obtain the same resin solids level per unit surface area, the solid resin content, expressed as a percentage of the oven-dry wood weight, has to increase. The experimental difficulty of quantitatively determining the surface area of a normal particle furnish, consisting of various configurations and particle volumes, is enormous; consequently, most researchers report the resin level on a weight basis (Turner 1954). Duncan (1974) has recently shown that larger particles receive proportionately more resin than the surface area they contribute to the furnish. He has developed a mathematical relationship between screen analysis data and relative surface area to show that the resin weight per unit of surface area is higher for larger particles than for small particles.

Post (1958, 1961), using surface areas of accurately cut flakes as the basis for resin treatment levels, found only moderate increases in bending strength when the resin treatment increased from 3.27 to 13.07 grams of resin solids per square meter of surface area. Post (1958) stated that using particle surface area rather than oven-dry wood weight as the basis for resin application appears to be a reasonable method of separating effects of particle geometry. This method was satisfactory for his controlled particle geometry, but in a normal furnish where there is a distribution of particle configurations, enormous difficulties are encountered in accurately determining the true surface area.

Maloney (1970) studied the resin distribution in layered particleboard by varying the resin level in the component layers while maintaining a constant resin content in the board. All of his data is on an oven-dry wood weight basis and, consequently, it is not surprising that the data show that fine particles received a disproportionate share of the resin. The sur-

face fines attained a 12 percent resin treatment as opposed to a 0.9 percent treatment for the core when the multi-layer board furnish was blended together. When 80 percent of the total resin was applied to only the core (larger) particles, followed by the addition of surface fines and the remaining resin, the surface particles had only a 4.0 percent resin treatment while the core resin content was 7.7 percent. Maloney (1970) also determined the surface area of 25 representative particles of each layer used for the multi-layer particleboard. Resin contents were then calculated on a particle surface area basis. These results showed that the resin content of the surface layer was slightly less than double that of the core when all layers were blended together. For the case where 70 percent of the resin was initially applied to only the coarser particles, the core resin content was approximately 3 times greater than the surface on a weight per area basis. Maloney concluded that about 8 percent resin solids by weight on the surface fines is sufficient for adequate bonding.

Maloney (1970) further concluded that an even distribution of resin by surface area is not the optimum condition for the production of multi-layer boards with high density surfaces and low density cores. He believed optimum conditions existed when a uniform distribution of resin by weight of particles was approached, because the high-density surfaces resulted in efficient usage of the applied adhesive; more adhesive per unit area was required in the low density core where the adhesive was not used efficiently. This is in direct contrast to Duncan's results (1974).

Lehmann (1970) reported data, obtained by screen analysis and reflectance measurements with a urea-formaldehyde adhesive containing a fluorescent dye, that show the smaller particles always have a larger percentage surface area coverage than the coarser particles when the two are blended together, regardless of whether a fine or coarse spray is used. Therefore, the fines had a higher resin content on an oven-dry wood weight basis but no data were presented as to the resin content on a surface area basis.

Istrate *et al.* (1964) have used a slenderness coefficient to describe the particle shape. Particles with high slenderness coefficients (length/thickness) could be satisfactorily glued into particleboards without requiring a continuous layer of adhesive, as was necessary for the particles with low slenderness coefficients. Thicker particles had less surface area per unit of weight but required more adhesive than did thinner particles. Istrate *et al.*

attributed this to the lack of contribution from the particle edges to the bonding mechanism. They reported a slenderness coefficient between 60 and 120 to be the optimum, depending upon the location of the chip in the particle mat. This agrees with the findings of Post (1961) in which the rate of increase in board strength decreased above a length/thickness ratio of approximately 100.

There appears to be no definitive literature available which conclusively proves exactly the location and distribution of adhesive in particleboard. On a weight basis, smaller particles consume more than their share of the adhesive, but opinions differ as to whether the consumption of adhesive on an area basis is greater or less for the smaller particles. Differences also exist as to whether it is desirable to have equal resin treatments, either on a weight or area basis, for different particle sizes. Further research on this problem is required.

Adhesive Type and Level

Adhesives currently used in particleboard manufacture consist of urea-formaldehyde and phenol-formaldehyde polymers. Phenol-formaldehyde usage is limited in this country since most particleboard is used in interior applications and urea-formaldehyde adhesives, which enjoy a large cost advantage, are entirely adequate for this use. The increased emphasis on structural-grade particleboard should provide impetus for the further development and utilization of phenol-formaldehyde or other durable adhesives in particleboard.

All investigators are unanimous in their findings that as the adhesive content increases all strength properties of the resultant particleboard increase. Consequently, this review will briefly cover adhesive variables such as reactivity, synthesis conditions, and type, as they have been reported to affect particleboard properties.

Deppe and Ernst (1971) produced particleboards with diisocyanate binders and obtained modulus of rupture (MOR) values at 2.5 percent diisocyanate comparable to those obtained at 3 percent phenol-formaldehyde (adhesive solids on OD wood). Press times for the diisocyanate are much shorter than the relatively long times for phenol-formaldehyde but the diisocyanate-bonded material stuck to cauls and other metal surfaces during manufacture. Schorning *et al.* (1972) attempted to develop new particleboard adhesives, both under alkaline and acidic curing conditions. Roffael and Rauch (1971a, 1971b, 1972b,

1973a, 1973b, 1973c, 1974) have studied the potential of sulfite liquor from the pulping process as an adhesive system for particleboards. They have also incorporated both phenol-formaldehyde resoles and novolacs with the liquor and various heating post-treatments to improve properties of the resultant boards. High temperature treatment of diisocyanate-bonded boards improved dimensional stability but lowered mechanical strength (1973c).

Anderson *et al.* (1974a, 1974b, 1974c) have studied the bark extracts of various species for potential particleboard adhesives. Bark extract as a possible adhesive source is an extremely active research area and a review of this field will not be attempted here. It does appear that bark extract offers a very good potential but further research is necessary to fully exploit this material.

Hse (1974a, 1974b, 1974c) has recently reported on a large study of urea-formaldehyde adhesives synthesized under various acidic and alkaline conditions with a number of formaldehyde/urea molar ratios at a series of different reaction concentrations and temperatures. Adhesives with a high methylol content produced boards with higher internal bond, modulus of rupture values. Resin shrinkage in curing was negatively correlated with the above properties but free formaldehyde content was linearly and positively correlated with these board properties. Hse (1974b) also made a series of urea-formaldehyde adhesives in which the methylolation pH was varied between 7 and 10 and the polymerization pH was varied between 3.8 and 5.8. Methylolation under neutral or slightly alkaline conditions produced adhesives which resulted in particleboards with higher internal bond and modulus of rupture values. Variations in the acidity had a smaller effect on the resins produced but the optimum was obtained when polymerization was accomplished at pH 5.8 following methylolation under neutral conditions. Hse (1974c) also found sodium hydroxide to be much better for catalyzing the methylolation reaction than either hexamethylenetetramine or triethanolamine. With sodium hydroxide as the methylolation catalyst, polymerization was possible with acetic acid, hydrochloric acid, ammonium chloride, and phosphoric acid, but with other methylolation catalysts the acid catalysts which produced satisfactory resins were limited.

Temperature is an important parameter controlling resin reactivity in particleboard production. Because heat has to migrate from the platens to the mat center in heated platen

presses, the longer the press cycle the higher the core temperature and more completely cured is the adhesive, as indicated by internal bond and thickness swell tests. Moisture migration to the core is also confounded with heat migration, as pointed out in the section "Vertical Density Gradient." Consequently, the temperature of the core does not rise significantly above 100° C until the liquid water has evaporated from the mat edges. Press temperature must be limited to prevent board surfaces in contact with the platens from being degraded; therefore, increasing the core temperature is normally accomplished by lengthening the press cycle. Because phenol-formaldehyde adhesives are not as reactive as the urea-formaldehyde adhesives, higher board temperatures are required, and this is reflected in longer press cycles for phenolic-bonded particleboard (Carroll 1963; Lehmann *et al.* 1973).

Roffael *et al.* (1972) found that raising the core temperature to 220° C, either by high frequency heating or extended press cycles, resulted in improved dimensional stability and internal bonds for phenolic-bonded Scotch pine particleboard.

Turner (1954) used a suspension of water-insoluble phenol-formaldehyde adhesive in his study of particle size and shape, and generally found that modulus of rupture increased, but at a decreasing rate as the resin content increased from 2 to 4 to 8 percent. Lehmann (1974) found an adhesive level of at least 1 pound of solids per 1,000 square feet of particle surface was required to produce optimum board properties with phenolic-bonded flakes 2 inches in length. This was approximately 5 percent adhesive (resin solids on OD wood) for this flake configuration. Lehmann *et al.* (1973) produced adequate 0.5-inch thick (40 lb/ft³) phenol-formaldehyde-bonded particleboard with a 2-minute press cycle at 375° F by adding moisture to the mat and catalyzing the adhesive. With these conditions and a 15-second press closing time, the core temperature was above 250° F in less than one minute. This they attributed primarily to moisture distribution and not press temperature or catalyst.

Kimoto *et al.* (1964) using urea-formaldehyde adhesive levels of 8, 10, and 15 percent (resin solids on OD wood), generally found only slight improvement in both strength and swelling properties with 15 percent as compared to 10 percent adhesive. The most notable exception to this was a greater than 50 percent reduction in thickness swelling for lauan particleboard when exposed to satu-

rated water vapor. The average particle dimensions used in this board were 2.172, 0.179, and 0.088 cm for the length, width, and thickness, respectively. None of the properties decreased as the resin content increased, but many properties were equal at either two or all three of the studied resin levels. Press times used in this study were exceptionally long (18 min.), the press temperature was only 130° C, and the particleboards were approximately 0.5 inch thick.

Post (1958) found that resin content has only a slight effect on the modulus of rupture (MOR) values with urea-formaldehyde adhesive spreads of 3.27, 6.54, and 13.07 grams per square meter (gm/m²) on flakes with a number of different configurations. Particle geometry was much more significant than adhesive content. Lehmann (1970) using a urea-formaldehyde adhesive at 2, 4, and 8 percent solids (resin solids on OD wood) found only small increases in MOR, modulus of elasticity (MOE), and thickness swelling when adhesive content increased from 4 to 8 percent, but the internal bond continued to increase substantially in this region.

Hann *et al.* (1963) reported improved particleboard durability when the adhesive level was increased from 3 to 6 percent and 4 to 8 percent for phenol-formaldehyde and urea-formaldehyde adhesives, respectively. They attributed this to the increased resistance of the board to springback with the additional adhesive content, Lehmann (1974) also reported much lower springback after accelerated aging when the phenol-formaldehyde adhesive content was increased to 3 from 9 percent (resin solids on OD wood).

Schuler (1974) made particleboard from chipping residues with seven levels of urea-formaldehyde adhesive ranging from 2 to 12 percent (resin solids on OD wood). No improvements were evident in MOR and MOE when the adhesive level was increased above 5 percent. For both properties, the 12 percent adhesive content was below the 10 percent level at all particleboard densities. The percent thickness swell, after both 2 and 24 hours water soak attained a minimum at 10 percent and were both higher at 12 percent adhesive content.

Clad (1967) found that high moisture content in the particle mat retarded curing of phenol-formaldehyde adhesives, whereas a low moisture content reduced the flow of the resin which reduced board quality. He also reported no improvements in board quality when the adhesive content increased above 12 percent.

Addition of a phenolic impregnating resin to the particles has been studied as a possible method for improving particleboard properties (Browne *et al.* 1966; Haygreen and Gertjens 1971). Haygreen and Gertjens (1972) made wafer-type particleboard with 3 percent phenol-formaldehyde adhesive and added 7 percent of an impregnating phenol-formaldehyde resin. Much better properties were obtained when the impregnating resin was added to green flakes instead of to the dry flakes. Thickness swelling and springback was significantly improved as was the strength and surface smoothness after one vacuum-pressure-soak cycle. Browne *et al.* (1966) used phenol-formaldehyde impregnating resin in both urea-formaldehyde- and phenol-formaldehyde-bonded particleboards. Impregnation reduced the irreversible particleboard swelling by either reducing the hygroscopicity or bulking the structure or, more likely, a combination of both. Obviously, the cost of producing this impregnating material severely limits the applicability.

There appear to be no consistent data available which indicate a particular adhesive level is optimum. Much of this inconsistency is due to the lack of uniformity in stating the adhesive content levels. Adhesive contents based on the oven-dry wood weight are extremely dependent upon particle configuration; however, the experimental difficulties inherent in determining the particle surface area per unit wood weight limits the usefulness of calculating spreads per unit of particle surface area. Consequently, each particle configuration will have an optimum adhesive content dependent upon the desired panel products and the economics of production. Multi-layer particleboard with different adhesive levels in the core and surface layers is one widely-used technique to obtain satisfactory board properties with the most economic use of adhesive.

Furnish

Most particleboard consists of over 90 percent ligno-cellulosic material on a dry weight basis; consequently, the properties of this raw material have a significant effect on both the manufacture and the physical properties of the final product. This section will briefly review the available literature pertaining to the effect of wood species and other ligno-cellulosic-based materials on properties of resultant particleboards. Specific effects on strength and dimensional properties will be more fully presented in these respective chapters.

The quality of wood furnish in particleboard manufacture is controlled by the species

properties such as density, acidity, extractive content, and machinability. The effect of wood density has been extensively studied and the general conclusion reached that species of lower density than the final particleboard density are required to economically produce high quality particle board (Larmore 1959; Vital *et al.* 1974; Hse 1975). This is believed to be related to the compressive failure previously mentioned.

Hse (1975) made particleboards of three densities with nine hardwood species using large flakes (3- by 3/8- by 0.015 inch) and a phenol-formaldehyde adhesive. He reported a compaction ratio (board density/wood density) of 1.25 required to obtain bending strength necessary for exterior particleboard applications. Thus, low-density species are required for low- to medium-density particleboard and high-density woods can only be high-density particleboard. However, thickness stability is inversely related to board density, severely limiting the potential of high-density particleboard.

Anthony and Moslemi (1969) reported satisfactory strength and dimensional properties for hickory flakeboard at 44 to 48 lb/ft³ (unspecified moisture content). Unfortunately, they do not state the density of the original hickory but most hickory species used in particleboard of the density would result in compaction ratios significantly less than 1.25.

Vital *et al.* (1974) produced three-layer particleboards from four exotic hardwood species of widely different densities. Boards with all combinations of one, two, three, and four species were made at each of two compaction ratios, 1.2 and 1.6. The properties of the particleboards with mixed species were primarily dependent upon the average density of the species mixture used and the bending strength could be predicted from the species mix. They also found that, with boards at equal densities, MOR and MOE were directly related to compaction ratio. This was attributed to the greater volume of wood compacted and the increased interparticle *contact*, which, combined, produced better bonding.

Other species variables are of only minor importance in determining species suitability for particleboard. Interior particleboard is produced with urea-formaldehyde adhesives which cure under acidic conditions. The acidity of the furnish should be monitored to allow proper adjustment of the catalyst level to prevent unduly long press cycles or precure of the mat before reaching the proper consolidation. Frequent species changes in the furnish should be avoided.

Extractives can also initiate or inhibit resin cure, but this effect can be corrected by catalyst adjustment. Non-hygroscopic extractives can also serve as a dimensional stabilizing agent, by either bulking the wood structure or inhibiting the adsorption of moisture.

There have been a number of studies to determine the potential of incorporating other ligno-cellulosic materials into particleboard. Rootwood (Howard 1974), sycamore saplings (Rice 1973), bark (Dost 1971; Gertjensen and Haygreen 1973; Anderson *et al.* 1974a, 1974b, 1974c), and forest residues (Heebink 1974; Lehmann and Geimer 1974) have all been studied as potential particleboard furnishes.

Slash pine rootwood particleboards made with large flakes and a phenol-formaldehyde adhesive had slightly better bending strength than, and twice the internal bond of, boards produced from stemwood (Howard 1974). The lower specific gravity of the rootwood resulted in a greater compaction at the same particleboard density, hence the better properties. However, grain deviation in the rootwood, as well as the greater compaction, resulted in poorer dimensional stability for these boards than was found in the stemwood boards.

Three-layer redwood particleboards, incorporating 0, 10, 20, and 30 percent redwood bark, were studied at three urea-formaldehyde resin levels (Dost 1971). Results show significant decrease in MOR, MOE, internal bond, and dimensional stability with increasing bark content at all resin levels. The 24-hour water absorption decreased as bark content increased, reflecting the lower hygroscopicity of the bark. Experimental difficulties were also encountered in blending the material; consequently, a part of the decreased properties may be due to a lack of adequate resin distribution.

Anderson *et al.* (1974a; 1974b; 1974c), in a series of studies on bark extract-bonded particleboard and particleboard with a bark core, have shown the potential of incorporating limited quantities of bark in extract-bonded exterior particleboard. Particleboards made with 100 percent bark had very low MOR and high linear expansion values, but particleboards with a bark core and wood surfaces were satisfactory for Ponderosa pine and white fir furnish. It remains to be seen if this bark core particleboard is suitable for general exterior applications.

Gertjensen and Haygreen (1973) studied the effect on the resultant physical properties of incorporating aspen bark in the furnish of wafer- and flake-type particleboards. A phenol-formaldehyde adhesive at 3 and 8 percent

was used for the wafer and flake boards, respectively. They concluded that the entire tree bole could be utilized for either particleboard type, provided the bark was removed from the butt log. The linear stability was drastically reduced when the butt log bark was included but bark from upper logs had little effect.

Rice (1973) showed the possibility of using young, fast-grown sycamore saplings for a flake-type particleboard. The only difficulty noted was the filtering of the bark fines to the lower surface of the mat. Rice (1973) believes this layering would be considerably reduced in mechanized mat formers and that whole-tree conversion of fast-grown sycamore saplings into flake-type particleboards of a variety of densities and resin contents is possible.

Chen *et al.* (1972) made particleboard from spruce with 100 percent total tree material (called biological surface mass) as well as using this material in combination with conventional debarked spruce furnish. Boards were of 8 percent urea-formaldehyde resin (resin solids on OD wood) and 0.5 percent wax (was solids on OD wood). Particleboards made with 100 percent total tree material did not meet standard bending specifications, but mixing this material with debarked spruce particles on an equal weight basis produced acceptable particleboards.

Stayton *et al.* (1971) reported that acceptable particleboards with 0.5-inch-long flakes could be produced from mixtures of high-density paper birch and low-density aspen with 8 percent urea-formaldehyde and 6 percent phenol-formaldehyde adhesives (resin solids on OD wood) at average densities of 45 and 46 lb/ft³, respectively. All-aspen boards were superior to boards containing birch but an all-birch board retained 80 percent of the strength of the all-aspen board. Stayton *et al.* (1971) reported the surface quality decreased with increasing birch but they believed acceptable particleboard could be produced with varying mixtures of birch and aspen flakes. Unfortunately, the density of the two species was not included in the above report.

Heebink (1974) and Lehmann and Geimer (1974) have produced structural, phenolic-bonded particleboard from forest residues of lodgepole pine and Douglas-fir, respectively. Heebink reported that structural particleboard could be produced from lodgepole pine forest residue greater than 3 inches in diameter. He also showed that a mixture of live and dead lodgepole pine forest residue would produce acceptable particleboard for overlaying

applications.

Lehmann and Geimer (1974) reported significantly lower panel properties when more than 12 percent bark was included in the furnish for particleboard produced from Douglas-fir forest residues. Panels composed entirely of tops and branches or less than 75 percent sound wood had even lower properties. The percent retention of the original properties was also determined after ASTM accelerated aging exposure. Excessive strength loss as a result of this exposure occurred in panels with 25 percent bark, 100 percent branchwood, and 100 percent decayed wood; panels with lower percentages of the above residues did not exhibit strength losses significantly higher than control boards.

Heebink *et al.* (1984) compared the quality of particleboard produced from planer shavings obtained with various planer settings. Planer shavings normally result in lower quality particleboard than that obtained from flakes. Consequently, this research was an attempt to improve the applicability of planer shaving for particleboard furnish by planer design modifications. Many of the changes effective in producing higher quality flakes reduced the quality of the planed surface or required substantial planer changes. However, the single most important variable which improved the particleboard quality was planing green stock; evidently the green particles did not crack as easily across the grain.

Lutz *et al.* (1969), using an experimental blanker to surface softwood lumber across the grain, showed the improved quality of the resultant flake, as opposed to planer shavings, for particleboard furnish. The flakes produced by this cross-grain cutting method resulted in particleboard properties equal to flakes from a disc flaker. These crossgrained flakes were not broken and curled along the grain as is common for planer shavings (Heebink *et al.* 1964).

Stewart (1970) reported on the high quality surfaces and flakes produced by cross-grain planing of hard maple and the wide variation of chip type available with a helical edge tool. Stewart and Lehmann (1973) produced particleboards with cross-grain, knife-planed flakes of four hardwood species; the boards showed exceptional linear stability. Stewart and Lehmann (1974) also showed the excellent strength and dimensional stability attainable in urea-formaldehyde-bonded particleboards from flakes produced by cross-grain cutting with helical cutters.

The material from which high-quality particleboard can be economically produced

is limited to those ligno-cellulosic materials of adequate inherent strength which can be readily broken down and glued together without unduly destroying the native strength. Cost, as influenced by resin content, is the controlling factor. Many ligno-cellulosics could theoretically be used for particleboard, but the higher adhesive contents required to obtain a satisfactory product are presently prohibitively high.

Pressing Conditions

The pressing operation is obviously an extremely critical step in particleboard production. It is during this step that many of the physical properties are determined, especially those properties influenced by the vertical density gradient. Mat moisture content, press closing speed, and press time and temperature are the most significant pressing conditions affecting the properties of particleboard.

Mat Moisture Content

The mat moisture content is an extremely critical factor not only for the total press time, but also in development of the vertical density gradient. As discussed earlier, the surface moisture evaporates and migrates to the mat center when the hot platens contact the mat. This speeds the transfer of heat to the core which allows the adhesive to react more quickly than if the heat moved by conduction through the wood and air spaces. However, excessive moisture migration to the core imposes the requirement of excessively long press cycles to allow removal of moisture through the edges to prevent delamination of the board upon pressure release. Excessive moisture also interferes with the chemical reaction of condensation polymerization, by which urea-formaldehyde and phenol-formaldehyde adhesives harden. Moisture at the mat surface also reduces the compressive strength of the wood and results in surface densification from compressive failure as the press is closed. Excessive surface densification results in low-density cores for a given average board density. The bending strength and tensile strength parallel to the board surface will increase as this densification occurs but the internal bond, interlaminar shear, and screw withdrawal will be lower as a result of the low-density core.

The method commonly used to circumvent the adverse moisture effects, but still retain the advantage of rapid heat transfer to the core, is a nonuniform moisture distribution through the mat thickness. With higher levels of moisture at the surfaces than at the core,

rapid heat transfer occurs without unduly lengthening the press cycle. This is readily accomplished in layered and homogeneous constructions in which the core material is dried and blended separately from the surface material. A homogeneous board with all material dried and blended in the same system can be given a nonuniform moisture distribution across the thickness by spraying the mat surface or cauls with water. Normally, a nonuniform moisture distribution, with the surfaces at a higher moisture content than the core, increases the vertical density gradient.

Maku and Hamada (1955) found a decreased thickness swelling and water absorption as the moisture content of the chips increased. However, it is unclear from the report whether the mats were pressed at high moisture contents or whether they were conditioned to 12 to 13 percent after blending at higher moisture contents.

Heebink *et al.* (1972) reported that a moisture distribution of 5 percent in the mat plus a 5 percent surface spray allowed the core to reach 220° F in a shorter time period than required for mats with a uniform moisture distribution of 10 percent for two different press temperatures and two different closing rates. However, the vertical density gradient data show a lower gradient for the boards with the uniform moisture content of 10 percent, although this comparison of density gradients is confounded with adhesive and press temperature differences. Heebink *et al.* (1972) reported 10 to 12 percent to be the optimum moisture content for mats with uniform distributions. Lower moisture contents required higher pressures to consolidate the mat and were characterized by poor interparticle bonding. Higher moisture contents necessitated longer press cycles to allow sufficient moisture to escape.

Heebink (1974) found that higher MOR MOE values for three-layer flakeboards than for those of an earlier study (unpublished) were partially due to a nonuniform moisture distribution. As opposed to a uniform distribution of 12 percent moisture content, a face and core moisture content of 15 and 5 percent, respectively, contributed to improved board strength.

Strickler (1959) showed that the time required for heating the mat core decreased with increasing surface moisture content. At higher surface moisture contents (above 15 percent) the MOR and MOE decreased when the core was at 9 percent moisture content. The internal bond also decreased but the thickness swelling improved as the surface

moisture content increased.

Strickler (1959) showed that the time required for heating the mat core decreased with increasing surface moisture content. At higher surface moisture contents (above 15 percent) the MOR and MOE decreased when the core was at 9 percent moisture content. The internal bond also decreased but the thickness swelling improved as the surface moisture content increased.

Kehr and Schoelzel (1965) also found a sharp decrease in the resistance of the mat to compression as increased quantities of water were sprayed on the mat surface. This, again, was the result of the reduced compressive strength of wood at higher moisture levels.

Lehmann (1960) found MOR values increased with increasing mat moisture to 13.4 percent moisture content, and then decreased at moisture contents of 16.5 and 20.0 percent. Internal bond increased as the moisture content decreased. Lehmann (1960) also showed an increased dimensional stability and a reduced water absorption as the mat moisture content increased. Rice (1960) used mat moisture contents of 9, 12, and 15 percent to study the effect of mat moisture on board properties. The MOR and MOE values were increased 18 and 13 percent respectively, by increasing the mat moisture content from 9 to 15 percent. Likewise, the dimensional stability of the panel improved substantially. The increased mat moisture content also reduced the closing time to stops with a constant pressure but the problem of thickness shrinkage in the press was greater with high moisture content mats. Gatchell *et al.* (1966) reported an optimum in static bending strength and internal bond at a moisture content of 12 percent.

The mat moisture content and moisture content distribution can be varied only within a rather limited range, hence the effect of this variable on particleboard properties is limited. With a uniform mat moisture content, the optimum range appears to be 11 to 14 percent. Much higher surface moisture contents are possible if the core region is at a correspondingly lower moisture content. Basically, it appears that the vertical density gradient is changed with changing moisture contents and distributions but the lack of vertical density gradient data prevents positive proof of this effect.

Press Closing Rate

Generally, the closing rate of most hot presses is established by adjustment of the initial pressure; higher initial pressures result in the platens closing to stops, or desired

thickness, more quickly than closing speeds attained at lower initial pressures (Kehr and Schoelzel 1967). Most authors, if they mention a closing speed, will normally give the information as the time to stops, which is the minimum time for exposure of the lower mat surface to the bottom platen before the mat has reached complete compaction. Time to stops is not the same as time of compaction: during the time from start of closing to loss of daylight between the mat and the upper platen no mat compaction occurs. The time of compaction as well as the total press closing time should be specified by researchers more frequently.

The closing rate of the press and the moisture content of the mat are both important factors in the formation of the vertical density gradient. Quickly closing the press will subject the mat surfaces to the platen heat and allow compressive failure at the mat surface before the interior has warmed sufficiently to allow distribution of the compressive failure through a greater portion of the mat thickness. Consequently, faster press closings would be expected to increase the vertical density gradient and improve the bending strength but at the expense of the internal bond and screw holding strength.

Rice (1960) reported improved MOR and MOE values as the closing rate increased but he found internal bond, springback, and swelling properties to be independent of closing times. Bismarck (1974) reported a reduction in internal bonds as the press closing speed increased above 40 in/min (inches per minute), but the bending strength continued to increase. He also reported that panels produced at the highest rate of compaction and with the shortest press cycle had the lowest formaldehyde emission. Bismarck developed a pressing technique in which the closing speed was related to the ratio of panel compression to the compressive resistance of the panel until desired thickness was attained. This technique prevented rapid compaction of a mat with low compressive strength which normally occurs with conventional press controls. Tests of his technique against the conventional procedure resulted in 5 and 9 percent improvements for bending and internal bond strength, respectively, a 10 percent reduction in thickness swelling, and a 16 percent reduction in pressing time. This technique most likely reduces the vertical density gradient although further studies are necessary to verify this.

Liiri (1969) monitored the pressure on a series of mats pressed with increasing closing times and found the maximum pressure re-

quired for mat consolidation decreased with increased closing times. The longer the mat was exposed to elevated temperature, the higher was the degree of wood plasticization and the lower the pressure required to compact it to the desired thickness.

Rice *et al.* (1967) reported decreasing internal bond values for flakeboard as the closing time of the press increased. Rapid press closure increased MOR, as expected, and substantially increased thickness swelling for uncatalyzed adhesives, but only slightly increased the thickness swelling for the catalyzed resin. The internal bond of flakeboards with both catalyzed and uncatalyzed adhesives dropped approximately 50 percent when the time to press closing was increased from 1.5 to 3.4 minutes.

Heebink *et al.* (1972) found the reverse relationship between internal bond and press closure time; i.e., as the closing time increased the core density increased and the internal bond increased. The lower face density with longer closure times also reduced the bending strength.

Maku and Hamada (1955) graphed thickness swelling versus pressure at various moisture contents and two chip thicknesses. A maximum thickness swelling occurred for all moisture contents and chip thicknesses at approximately 20 kg/cm² (kilograms per square centimeter) (284 lb/in.²). Unfortunately, experimental details are not given; it appears that the mats were not pressed to constant thickness but instead the various pressures resulted in boards of various specific gravities. Consequently, their data may be confounded with density effects.

Geimer *et al.* (1975) have recently published vertical density gradients obtained from 0.85-inch-thick three-layer boards at three different closing speeds. Extremely fast closure (20 seconds) resulted in a continuously decreasing density from the surface to the core. One-minute closure time produced a maximum density approximately 1/16 inch below the surface while the 3-minute closure time resulted in a vertical density gradient with a board peak from approximately 0.1 to 0.2 inch below the surface. The maximum of the 3-minute gradient was at a substantially lower density than the maximum for the 1-minute closure time.

The effect of press closure speed on the properties of particleboard appears to be fairly well established. The press closure rate influences the properties related to the vertical density gradient since this is highly dependent on closing speeds. Press closing rates can be

adjusted to optimize the desired properties, but adjustments have to be within fairly narrow boundaries as dictated by the resin reactivity and mechanical limitations of the press.

Press Time, Temperature, and Pressure

The function of the hot press in particleboard production is to consolidate the chip mat to the desired thickness and density followed by polymerization of the adhesive between adjacent chips into a cross-linked solid polymer to hold the mat in this consolidated state when removed from the press. To facilitate the chemical reaction and allow reasonable press times, all production presses in the particleboard industry employ some method of heating the mat. Most commonly, this is done by heated platens which contact the mat surfaces. Heat then flows from the platens through the mat surfaces into the interior. Because the entire board is not uniformly heated throughout the thickness, the curing of the adhesive does not occur uniformly; the adhesive at the mat surface is the first to cure and that at the central region the last. Because the mat center is always at the lowest temperature, the pressing time and temperature should be such to ensure that the core reaches a sufficiently high temperature to allow the resin to cure. This can be accomplished by increasing the press time at a constant temperature or by increasing the press temperature at a constant pressing time.

Particleboard produced in presses equipped with a high frequency generator are heated more uniformly because heat is generated within the mat and does not migrate from the hot platens. The adhesive cures much more uniformly through the thickness and the mat center is not any cooler than the remainder of the mat.

Superimposed upon the requirement of reaching a given core temperature is the effect of moisture migration to the core. The press time has to be sufficiently long to allow excess water to migrate to the board edges before termination of pressing. A board with a properly cured center will delaminate upon pressure release if the steam pressure is higher than the internal bond of the particleboard (Lehmann *et al.* 1973).

Lehmann *et al.* (1973) found that, with a catalyzed urea-formaldehyde adhesive, a centerline temperature above 200° F for 0.25 minute was sufficient to cure the adhesive. The rate of heat transfer to the center controlled the total pressing time for a given board; therefore, shorter press times were obtained with higher press temperatures, "steam shock"

treatments, and thinner boards.

In the same study, phenol-formaldehyde resins were found to have a slower curing rate than the urea-formaldehyde binders. In this case, 1.75 minutes above 220° F was required to satisfactorily cure the adhesive in the core. The catalysts used in this study (methylethyl ketone hydroperoxide, potassium chromate, and phenol-resorcinol resin) were not effective in reducing press times of the phenol-formaldehyde adhesives. The data appeared to indicate that phenol-formaldehyde adhesives are much more adversely affected by high moisture levels in the curing zone than are the urea-formaldehyde resins.

Otlev (1971) reported the moisture content of particleboard core and surfaces after pressing to be 11 to 13 percent and 3 to 5 percent, respectively. Moisture sprayed on the surface did not produce a higher center moisture content but did speed the rate of resin curing.

Heebink *et al.* (1972) reported satisfactory urea-formaldehyde-bonded particleboards could be produced when the center temperature was above 220° F for 0.5 to 0.7 minute. They also reported a decrease in total pressing times of 1 to 2 minutes when the press temperature was increased from 375° to 475° F. This higher temperature allowed faster heat transfer and shifted the maximum density region toward the interior, so the internal bond strength increased and the bending strength decreased.

Liiri (1969) reported a decrease in the maximum pressure required to compact the mat as the press temperature increased. This is the result of increased plasticity of the wood as the temperature increases.

Lynam (1959) stated that longer press cycles at lower temperatures were desirable because less water was removed from the board and the subsequent moisture adsorption from the atmosphere was reduced. Long press cycles also allowed more water to escape but Lynam (1959) believed long cycles at lower temperatures were better than short cycles at higher temperatures, because less water was evaporated and the remaining water was more uniformly distributed in the finished board. He has no experimental data in this report on which to base his conclusions.

The effect of platen temperature on compression time for three-layer particleboards has been studied by Kehr and Schoelzel (1965) at three moisture contents. Increasing the platen temperature from 120° to 180° C rapidly reduced the compression time required for a mat moisture content of 11 percent. However,

very little change in compression time with temperature was evident at 18 percent moisture content, although the compression time was lower than that of the 11 percent mat. This indicates that wood at 18 percent moisture content is sufficiently plasticized for compression and that additional plasticization imparted by the heat is not required.

Lehmann (1960) used three press temperatures (227, 307, and 344° F) to study the effect on dimensional and strength properties of yellow poplar flakeboard. The extremely long press times employed (20 to 45 minutes) probably allowed complete cure of the adhesive in all cases and may account for the lack of significance of press temperature on most properties. Thickness of the board out of the press was significantly decreased as the press temperature increased, probably due to increased drying and subsequently higher shrinkage.

Pressing time and temperature are extremely important parameters in particleboard manufacturing and have to be carefully controlled to ensure that the core temperature attains the level required to cure the adhesive without subjecting the board surface to a high, degradative temperature. Improvements in particleboard adhesive technology have significantly lowered the time period required to cure the adhesives and have allowed the industry to attain relatively short press cycles. Therefore, the press temperature and pressing time need to be closely controlled to ensure adequate temperature levels are reached in the core at the most economical combination of these two factors.

Press pressure is of minor importance in particleboard produced with press stops, once the initial mat consolidation is reached. Kehr and Schoelzel (1965) produced particleboards with reduced pressure at various time intervals after the desired thickness was reached. No significant property deterioration occurred when the pressure was released after 2 minutes on stops for the boards at 0.65 gm/cm³. The higher density boards (0.70 gm/cm³) exceeded the desired thickness and had slightly lower internal bond when the pressure was reduced after 2 minutes.

Liiri (1969) measured the pressure within the board as a function of press time and found a sharp maximum occurred at the point at which target thickness was attained. This was followed by an immediate drop to a very low pressure at the end of the press cycle. This pattern was obtained at all board densities and all closing times although the maximum pressure was higher for the higher density

board and occurred at later times as the closing time increased. Therefore, the pressure in the board increases quickly during mat compaction and decreases once the thickness is obtained, at which time the press pressure can also be reduced.

Lehmann *et al.* (1973) obtained similar results of board pressure versus press time with catalyzed urea-formaldehyde Douglas-fir flakeboards. The pressure diagrams for three thicknesses of 40 lb/ft³ boards were nearly identical; a maximum pressure of approximately 600 lb/in.² was obtained at a press time of 1 minute. The 45 and 50 lb/ft³ boards attained a pressure of approximately 850 and 950 lb/in.², respectively, at a press time of 1 minute. Heebink *et al.* (1972) found similar sharp decreases in the board pressure and concluded that the minimum press time could be determined as the point at which the required pressure fell below the internal bond strength of the board.

Until further improvements in press technology are realized, the practice of controlling particleboard thickness with stops in multi-opening presses will continue. Hence,

the function of the pressure is to bring the component particles into intimate contact by consolidating the mat to the thickness of the stops. Once stops have been reached, further additional pressure is useless and, in fact, it has been adequately shown that the pressure can be reduced as the pressing operation continues. The only influence press pressure has on the resultant panel properties is related to the speed of closure and its effect on the vertical density gradient, assuming platen contact on the stops continues throughout the press cycle.

One further pressing technique, which has appeared in the literature, is the injection of high pressure steam into the consolidated mat in the hot press (Shen 1973). The steam reportedly cured the phenol-formaldehyde adhesive very rapidly and the resultant particleboard possessed superior dimensional stability and strength properties compared to a conventionally platen-heated board. Further research and development are required to fully study this method before it is widely applied in industry.

STRENGTH PROPERTIES

The various processing parameters have various effects on the resultant panel strength properties. A number of difficulties are encountered when reviewing the literature for this information.

Foremost of these difficulties are the reports which do not furnish sufficient information as to experimental procedures and conditions. Many instances were found in which important processing parameters, such as mat moisture content and distribution, rate of press closing, and particle configuration, were not given. As pointed out in the vertical density gradient section, the above variables are extremely important in controlling this gradient, and bending and internal bond properties are strongly influenced by this gradient.

The effects of interaction between processing variables on the resultant properties are normally quite large and in many instances separation of these interactions proved to be impossible. The moisture content of the board at test has been shown by Halligan and Schniewind (1974) to have a significant effect upon the modulus of rupture, modulus of elasticity, and internal bond. Some reports, however, do not include the moisture content at which the various tests were conducted.

One further difficulty is the applicability of laboratory research results to the particleboard production line. Optimum, well-controlled production conditions in the laboratory often are not duplicated on the production line due to the desire to keep production at the highest possible level or due to lack of proper equipment maintenance. Consequently, most laboratory-produced particleboards will have higher strength values than those obtained from a production line with the same furnish and adhesive content. An example of this is the commercial blender, which operates at rates above those shown to produce optimum blending (Carroll and McVey 1962). Another example is moisture migration to the board edges in the hot press; in small laboratory-produced boards, migration will occur in less time than in large production-size boards. Therefore, commercial press times are normally longer than would be predicted from laboratory results. Mat felting is normally more uniformly accomplished in commercial production than is possible with hand felting in a laboratory. Consequently, density variations across the board are normally less pronounced in commercial products.

The information reviewed here was obtained from tests conducted on laboratory-

produced boards, but the trends and conclusions should also apply to commercial products. The literature, on the effects of board density and particle configuration and orientation is reviewed for each major strength property. Variables which have been reported to affect a number of properties will be discussed separately in the respective strength property section. Literature pertaining to other processing parameters, such as adhesive content, moisture content, and pressing conditions, which affect the panel strength properties can be found in the section, "Processing Parameters."

Bending Strength

The bending strength of particleboard is measured on the ASTM Standard Method D 1037 for static bending. The four strength properties obtainable from this test (ASTM 1975) are the (a) modulus of rupture; (b) modulus of elasticity; (c) stress at proportional limit; and (d) work at maximum load. The modulus of rupture is the most widely determined property from static bending tests of particleboard. The modulus of elasticity, or stiffness, is much less often determined and stress at proportional limit and work to maximum load are rarely encountered in the literature.

Modulus of Rupture

The modulus of rupture (MOR) is an important property determining the applicability of particleboard for structural components. Many processing parameters and their effects on the MOR have been studied; the most widely reported parameters are board density and particle configuration and orientation.

Density.--The density of the board divided by the density of the wood equal the compaction ratio (Hse 1975). Hse illustrated a high correlation between compaction ratio and MOR for particleboards at three different densities produced from nine hardwood species from low to high specific gravity. Unfortunately, the equation presented to fit the plot of MOR versus compaction ratio does not fit the data (Hse 1975). Figure 1 of that paper, erroneously entitled MOE instead of MOR, has a linear equation which gives an excellent fit to the data but a minus sign before the intercept has been omitted. The plot of the experimental points does appear to illustrate an excellent linear relationship between modulus of rupture and compaction ratio for all species used in this study.

The compaction ratio has been practically

ignored by most researchers in particleboard technology; many make reference to the necessity of compacting the material to a density greater than the original wood, but few have actually calculated a compaction ratio. The board density used in the calculation is the average board density; therefore, comparing the relationship of MOR to compaction ratio between researchers is useless unless similar vertical density gradients are present in the respective boards.

Howard (1974) determined the densification (compaction) ratio for flakeboards made from slash pine stems and root material. The MOR for boards made from the root material was higher than the same-density board from stemwood and, since the density of the root material was less than the stemwood, the compaction ratio was higher for the root material.

Vital *et al.* (1974) found that particleboards from four exotic hardwoods of widely varying specific gravity, made to constant board density, had higher MOR values as the compaction ratio increased from 1.2 to 1.6. However, boards made to the same compaction ratio from different furnish specific gravities did not result in constant MOR values, as reported by Hse (1975), but increased linearly with increasing board density.

Stewart and Lehmann (1973) found the MOR to increase linearly with increasing panel density for four hardwood species ranging in specific gravity from 0.37 to 0.67 (OD weight, volume at 8 percent moisture content). However, the modulus of rupture decreased as the species density increased--i.e., as the compaction ratio decreased--for all board densities.

Stegmann and Durst (1965) have illustrated (fig. 12) the relationship between the MOR values for particleboards of different densities produced from furnishes of various wood species with different densities. As the furnish density increases, the MOR values decrease at constant particleboard densities, although a sharper drop in the MOR at low board densities and high wood densities would be expected than shown by this curve.

Obviously, compaction ratio is directly proportional to the particleboard density for furnish with constant specific gravity. All studies in which board density versus MOR has been determined report an increase in modulus of rupture with increasing board density--that is, as the compaction ratio increases the modulus of rupture increases. Consequently, compaction ratio may be an excellent method of quantitatively determining the relationship between board density and modulus of rupture. Determining the furnish

specific gravity is necessary in order to calculate the compaction ratio; this practice will also result in additional benefits to the particleboard literature, which is currently lacking in furnishing specific gravity data.

Further research is required to determine the feasibility of using compaction ratio as a predictor for the MOR of particleboard. Compaction ratio alone is not the only factor influencing the MOR values; pressing conditions, adhesive content, and many other processing factors are extremely important, but the compaction ratio warrants further study.

It is unanimously accepted, and adequate evidence is available, that MOR increases with board density when all other factors (particle configuration and orientation, species, adhesive content, pressing conditions, etc.) are

constant. The reviewed literature does not have any reported decrease in modulus of rupture when average board density increases.

The surface density strongly affects MOR because bending stresses are higher at the surfaces. Consequently, MOR values are highly dependent upon the vertical density gradient; widely different values can be obtained for equal average board densities simply by changing the processing variables affecting the vertical density distribution. Rice (1960) increased the MOR 18 percent by increasing the mat moisture content into the press from 9 to 15 percent for sweetgum flakeboard. Lehmann (1960) reported similar results with yellow poplar furnish but noted a decrease in MOR when the moisture content was increased from 16.5 to 20 percent. Higher moisture contents increase the compressibility

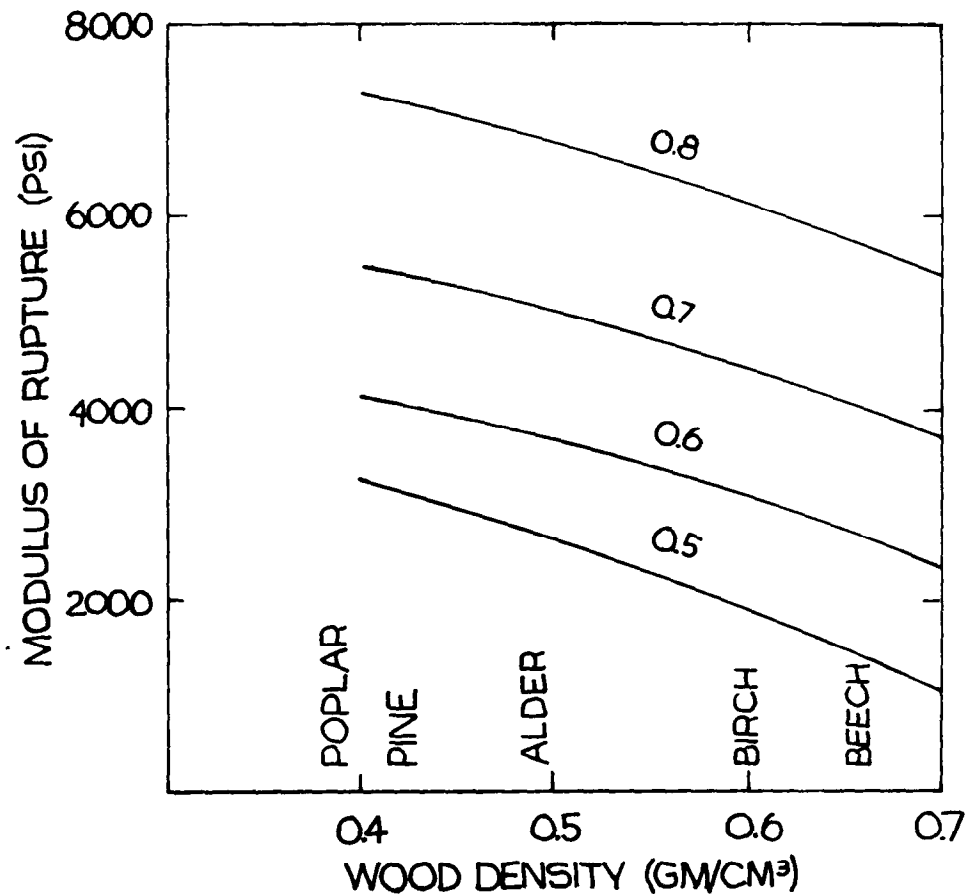


Figure 12.--Relationship between wood density and modulus of rupture for four particleboard densities.

(From Stegman and Durst 1965)

It is recommended that these curves be used with care, as a board density of 0.5 is not currently possible with wood of 0.6 density.

(M 144 412)

of the mat surface during press closing, resulting in increased surface densification and higher MOR values (Strickler 1959; Heebink *et al.* (1972). The adverse effect of high uniform mat moisture content on press time and adhesive hardening is reduced by adding the moisture to the surfaces and not to the core.

Kehr and Schoelzel (1967) reported no clear effect of press closing speed on the vertical density gradient or MOR values. However, Heebink *et al.* (1972) found a definite surface densification increase as the closing speed increased and a direct relationship between MOR and surface density. Therefore, it appears that useful information could be obtained by determining the vertical density gradient, as well as the average board density, and relating it to MOR values, as recently proposed by Plath and Schnitzler (1974).

Particle configuration and orientation.--

Many reports appear in the literature on studies concerned with the effect of particle geometry and alignment on the resultant particleboard strength properties. The difficulty in reviewing these and finding a consensus of the optimum particle size for maximum MOR, or any other property, is the nonuniformity of the other variables used in the studies. Species, average board density, adhesive type and amount, as well as pressing conditions affecting the vertical density gradient, are not constant. However, the many reports available do allow useful comparisons. It should be remembered that the particle size for optimum MOR is not necessarily the optimum for dimensional stability or internal bond; compromises in particle geometry have to be made to produce boards which have satisfactory properties to fulfill desired end-use functions.

Turner (1954) published results of one of the first investigations on particle size and shape and the influence of these on the strength properties of particleboard. Four particle configurations--flat flakes, thin strands, helical ribbons, and cubes--were glued into panels of 0.5 to 1.05 specific gravity with 2, 4, and 8 percent phenol-formaldehyde adhesive. Equal weights of blended material were pressed in a mold at 250, 500, and 1,000 lb/in.² to obtain the various densities; consequently, panel thickness was not constant. At a constant panel density, the flakes 3 inches long and 0.015 to 0.020 inch thick had the optimum MOR values.

Post (1958) found a continuous increase in MOR for oak particleboard with increasing flake length over the studied range of 0.5 to 4 inches, but the rate of increase decreased with lengths greater than 2 inches. However, as the

flake thickness increased above 0.010 inch, MOR decreased for all flake lengths. The flake length/thickness ratio was found by Post (1958) to be closely related to MOR at all flake lengths and thicknesses. MOR continued to increase but only slowly even at the highest ratio (300) used in the study. In a related study, Post (1961) stated that the length/thickness ratio is a better indicator of the effect of particle configuration on MOR than either dimension individually.

Brumbaugh (1960) studied the effect of flake size on Douglas-fir particleboard of three densities. Modulus of rupture values increased with increasing flake length within the studied range of 0.5 to 4 inches. Flake thicknesses of 0.009 to 0.018 inch resulted in no significant effect on MOR. Brumbaugh indicated optimum overall board properties required a length/thickness ratio of at least 400, but his reported MOR values increased as the ratio increased to 250 and remained constant at higher ratios.

Heebink and Hann (1959) studied the effect of particle shape on homogeneous particleboard properties of northern red oak; their results also showed 1-inch flakes to have significantly higher MOR values than 0.25-inch flakes, at an equal thickness of 0.015 inch. Planer shavings, sawdust, slivers, and fines all resulted in lower MOR values than did the 0.25-inch-long flake.

Kimoto *et al.* (1964) made low-density (specific gravity 0.3 to 0.4) particleboard from three configurations of lauan flakes and splinters with length/thickness ratios of from 10 to 100. The highest MOR values were obtained at the highest ratio for both particles, but the results with the splinters were not statistically significant. The flake length/thickness ratio was highly significant; MOR increased with increasing ratios even up to the highest ratio (100). Rackwitz (1963) also reported optimum strength values achieved at ratios of from 100 to 130 with particles up to 0.75 inch long. Heebink (1974), with a constant length/thickness ratio (100), found higher MOR values for the boards produced with flakes 2 inches long than with flakes 3 inches long.

Lehmann (1974) found increasing flake thicknesses always reduced MOR, when other factors were constant for phenol-formaldehyde bonded flakeboard for structural applications. Gatchell *et al.* (1966) found an increase in MOR as flake thickness decreased with phenolic-bonded flakes. Flake length (1 and 2 inches) did not greatly affect the MOR. Planer shavings resulted in reduced MOR values. Stewart and Lehmann (1973) reported very

little effect of flake thickness on MOR in the thickness range of 0.006 to 0.018 inch for particleboard from four hardwood species. Talbot and Maloney (1957) studied particleboards made from coarse and fine planer shavings at three board densities with three levels of wax and powdered phenol-formaldehyde adhesive. The coarse shavings (retained on 4 mesh screen) resulted in higher MOR values than the fine shavings (passed 4 mesh, retained on 16 mesh screen) for all resin and wax levels at all board densities used.

The available literature seems to indicate that particle thickness has more influence on MOR values than does particle length, at least at lengths greater than 1 to 2 inches. At those lengths, significantly lower MOR values have been found as the particle thickness increases above 0.020 inch. The above studies in which the length/thickness ratio influence on the MOR values have been reported were normally conducted by holding one particle dimension constant. This allowed comparisons of MOR for particleboards with component particles of different length/thickness ratios. The various investigators differ as to the optimum ratio, but all appear to agree that MOR increases with an increasing length/thickness ratio. Heebink (1974), holding the ratio constant by changing both dimensions, concluded that increasing the particle thickness from 0.02 to 0.03 inch had a more detrimental effect on the MOR than decreasing the particle length from 3 to 2 inches. Hence, it appears that much of the literature indicating a relationship between particle length and thickness is, in fact, illustrating the possibly more important effect of particle thickness.

Very few studies have been conducted relating the MOR to the particle width. Kusian (1968) found MOR increased as the width increased, but as the width approached particle length the MOR decreases. Suchsland (1959) stated that the ideal particle configuration for a three-layer particleboard was narrow, thick particles in the core and thin, short, square particles at the surfaces. This, according to Kusian (1968) will not optimize the MOR property, but the square particles should result in a smoother surface.

Hse *et al.* (1975) have recently published results of a study with layered particleboard made from flakes 3 inches long, consisting of equal portions of hickory, white oak, southern red oak, sweetgum, and southern pine. (This paper has the same graph of MOR versus compaction ratio Hse had published earlier (1975) with the minus sign missing from the intercept term of the regression equation.)

Unfortunately, Hse *et al.* presented no data on face-core proportions so a 20 percent reduction in MOR resulting from random face orientation when compared to aligned face orientation (both on random cores) is difficult to interpret. Geimer *et al.* (1975) have presented data which indicate face orientation perpendicular to test direction results in MOR values only half those obtained when the face flakes are aligned parallel to the long dimension of the test specimen. This result is based on 1/2-inch board with approximately 40 percent of the total board weight in the faces.

Klar and Stofko (1965) studied different surface thicknesses of oriented and unoriented particles with sawdust cores, at constant board thicknesses. They found increasing MOR values with decreasing core thickness (increasing surface proportion). Klautitz *et al.* (1960), using oriented particles approximately 2 inches long throughout the entire thickness, found MOR values in both grain directions to be at least as strong as wood, up to a density of 0.6. The inherent weakness of wood in bending perpendicular to the grain was greatly exceeded by the aligned particleboard when tested perpendicular to the particle alignment, indicating completely aligned particleboard does not have as large differences in bending strength between the two directions as is common for wood.

Larger particles can also be satisfactorily bonded at lower resin contents, because the particle surface area is drastically reduced as the particle size increases. Gertjeansen and Haygreen (1973) indirectly show the advantage of 1.5-inch-long wafers over 0.5-inch flakes on phenol-formaldehyde adhesive consumption when producing homogeneous particleboards with the respective particles. The MOR was reduced approximately 9 percent when wafers were used instead of flakes from the same wood source. However, the adhesive content of the waferboard was only 3 percent as compared to 8 percent (resin solids on OD wood) for the flakeboard; consequently, tremendous adhesive savings are possible with the larger wafer, providing other properties are maintained.

The effect of particle geometry on the resultant panel MOR values appears to be fairly well established. Particles of high length/thickness ratios, in which structural damage is minimal, normally produce particleboards with superior MOR values. Planer shavings are usually damaged and consequently produce a board with inferior MOR values (Hart and Rice 1963; Heebink *et al.* 1964). Large particles at the board surface normally do not felt as well

or produce as smooth a surface as smaller particles. Consequently, a balance has to be established between modulus of rupture and other board properties; one widely used compromise is a three-layer construction in which small particles, for smoothness, are used for particleboard surfaces and larger particles, with less adhesive, are used in the core.

Modulus of Elasticity

The modulus of elasticity (MOE) is an important property because it is a measure of the stiffness, or resistance to bending, when a material is stressed. The effective MOE of particleboard is measured by mid-span loading as described in ASTM D 1037 (1975). The nonuniformity of platen-pressed particleboard in the thickness direction prevents the determination of a true MOE. Effective MOE used here is board stiffness divided by moment of inertia -- *i.e.*, EI/I .

In general, modulus of elasticity and modulus of rupture are affected similarly by various processing parameters. Increasing board density increases both properties; increasing surface density and surface particle alignment increases both properties; and higher adhesive contents normally increase MOR and MOE. Howard (1974) and Vital *et al.* (1974) have calculated regression equations for MOE versus MOR values for the data of their respective studies. Howard (1974) presents regression equations for boards from both stemwood and rootwood of slash pine made with 3-inch-long flakes. The scatter for these equations is large, especially for the stemwood material ($r^2 = 0.22$) whereas Vital *et al.* (1974) obtained highly significant correlations ($r^2 > 0.96$) for regression equations at the two compaction ratios studied with 3/4-inch-long flakes. The regression equations of each paper predict widely different MOE values, so comparisons are useless. This is not unexpected as the flake length strongly affects the bending strength; consequently, the respective regression equations are not applicable to particleboards produced with processing variables at levels other than those at which the equations were calculated.

The effective MOE is not determined as frequently as MOR by various researchers; consequently, there are many reports in the literature in which no information is available on MOE. As was done in the section, "Modulus of Rupture," the parameters affecting MOE will be reviewed individually in the following density and particle configuration and orientation subsections.

Density.--Particleboards of constant aver-

age density possess higher MOE values as the wood density decreases -- *i.e.*, as the compaction ratio increases. Hse (1975) plotted MOE versus compaction ratio for phenol-formaldehyde-bonded particleboards from flakes of eight different hardwoods with widely different wood densities. The rapid increase in MOE with increasing compaction ratio was highly significant. The regression equation fitting this data predicted an MOE of 670,000 lb/in.² at a compaction ratio of 1.0, and 800,000 lb/in.² at a compaction ratio of 1.24. The excellent correlation between MOE and compaction ratio found in this data should not be extrapolated to other studies unless the processing parameters are the same as in Hse's study.

In contrast to Hse, Vital *et al.* (1974) used two compaction ratios with various mixtures of four exotic hardwood species to produce particleboards of various densities. Within a compaction ratio, a highly significant linear relationship was obtained between effective MOE and board density. Hse's (1975) graph indicates that any given value of MOE has only one compaction ratio, independent of board density, while Vital *et al.* (1974) indicate that for a given MOE, a compaction ratio of either 1.2 or 1.6 is possible, depending upon the board density. However, no direct comparisons should be attempted between these studies: Hse (1975) used large flakes (3 inches long) and 4 percent phenol-formaldehyde adhesive while Vital *et al.* (1974) used smaller flakes (3/4 inch long) and 7 and 9 percent urea-formaldehyde adhesive in core and surface layers, respectively (resin solids on OD wood). This lack of uniformity illustrates the difficulty in comparing individual reports.

The vertical density gradient, as influenced by face weight/total board weight ratio and press closing time, has been shown by Geimer *et al.* (1975) to have a tremendous influence on the effective MOE, even at a constant board density. Consequently, unless the vertical density gradient is determined and its effect recognized, erroneous conclusions can be drawn about the effect of other variables, such as particle configuration and resin content, on the effective MOE. Most researchers attempt to circumvent the vertical density gradient effect by using a constant press closing rate, press temperature, and mat moisture content. The effectiveness of this practice, when various levels of a particular process parameter are studied, has not been reported in the available literature. Until the practice of determining vertical density gradients is more widespread, many properties reportedly due to

processing changes may be, in reality, due to the vertical density gradient effect.

Lehmann (1970) reported the effective MOE to be significantly affected by board density for particleboard produced from Douglas-fir flakes with 2, 4, and 8 percent adhesive (resin solids on OD wood). There was also a significant resin content-density interaction indicating more efficient resin usage at the higher densities. Shuler (1974) and Lehmann (1974) found a linear relationship between MOE and density at all resin contents studied.

Heebink *et al.* (1972) measured the vertical density gradient and MOE for particleboard pressed with 5 and 15 percent moisture content in the core and surfaces, respectively. The high density regions within 1/16 inch of the surfaces resulted in high effective MOE values. Plath (1971b) showed mathematically the relationship between MOE and density of various layers through the thickness direction. He presented an equation from which the MOE can be calculated if the vertical density gradient is known and also pointed out the optimum gradient for maximum MOE is a relatively high-density surface. Bismarck (1974) reported an increase in MOE as the speed of press closure was increased from 15 to 30 mm/min. This also demonstrates the influence of the vertical density gradient and the improvement possible in the effective MOE with higher density surfaces.

The literature contains many studies which report a direct relationship between board density and the effective MOE; all unanimously agree that an increase in density will increase MOE. No general quantitative relationship is obvious between studies, as very few reports are complete enough in the processing details to allow comparisons. For example, very few reports contain mat moisture content into the press, press closing speed, and all other pressing conditions to allow comparisons with other reports. Two investigators can report widely different MOE values for the same average board density or resin content, but no comparisons can be made because the experimental details are missing.

Particle configuration and orientation.--

The modulus of elasticity is strongly dependent upon flake length; longer flakes produce particleboards with substantially higher effective MOE (Heebink and Hann 1959; Heebink *et al.*, 1964; Lehmann 1974).

The effect of particle thickness on MOE does not appear to be as well defined as the effect of length. Stewart and Lehmann (1973)

did not find a significant effect of flake thickness on the effective MOE for particleboards produced from cross-grain flakes in the thickness range 0.006 to 0.018 inch. Gatchell *et al.* (1966) found an increase in MOE when flake thickness decreased from 0.030 to 0.015 to 0.007 inch. Rackwitz (1963) found the optimum MOE with a length/thickness ratio range of 100 to 130; the MOE increased as the ratio increased to this range and remained constant at higher ratios. Particle width was reported to have only a slight influence on MOE. Lehmann (1974) also found a decrease in the effective MOE when the flake thickness increased from 0.030 to 0.045 inch, at a constant flake length of 2 inches and at all phenol-formaldehyde adhesive contents studied.

The effect of surface particle alinement on MOE is similar to the effect on MOR, as discussed in that section. Geimer *et al.* (1975) have shown that, for a constant average board density of 40 lb/ft³, the effective surface MOE increases at a faster rate above a face specific gravity of 0.75. Below a face specific gravity of 0.75, the rate of increase in surface MOE with increasing face specific gravity is approximately constant (fig. 13). The increasing rate above 0.75 face specific gravity occurs with random as well as with alined surface flakes, although the effective MOE values are substantially higher for boards of parallel alinement. This again illustrates the influence of the vertical density gradient on particleboard MOE values as well as the benefit of surface particle alinement. At a surface specific gravity of 0.7, the particleboard with parallel alined surface flakes had approximately 2.5 times the effective MOE of the random surface and approximately 14 times the effective MOE when determined in the direction perpendicular to the surface flake alinement. This data illustrates the large differences possible in MOE values for a constant average board density simply by changing the vertical density gradient. This further strengthens the argument for determining the vertical density gradient when measuring various strength properties.

Maloney (1975), in a study to determine the effect of short-retention-time blenders on large flake furnishes, found an increase in MOE as the board specific gravity increased for all resin levels studied (2, 4, and 6 percent resin solids on OD wood). Negligible improvements in the MOE at all board specific gravities were obtained on increasing the resin content from 4 to 6 percent. Hse *et al.* (1975) also obtained significantly higher MOE values at all board densities with alined surfaces on random cores as opposed to random surfaces on

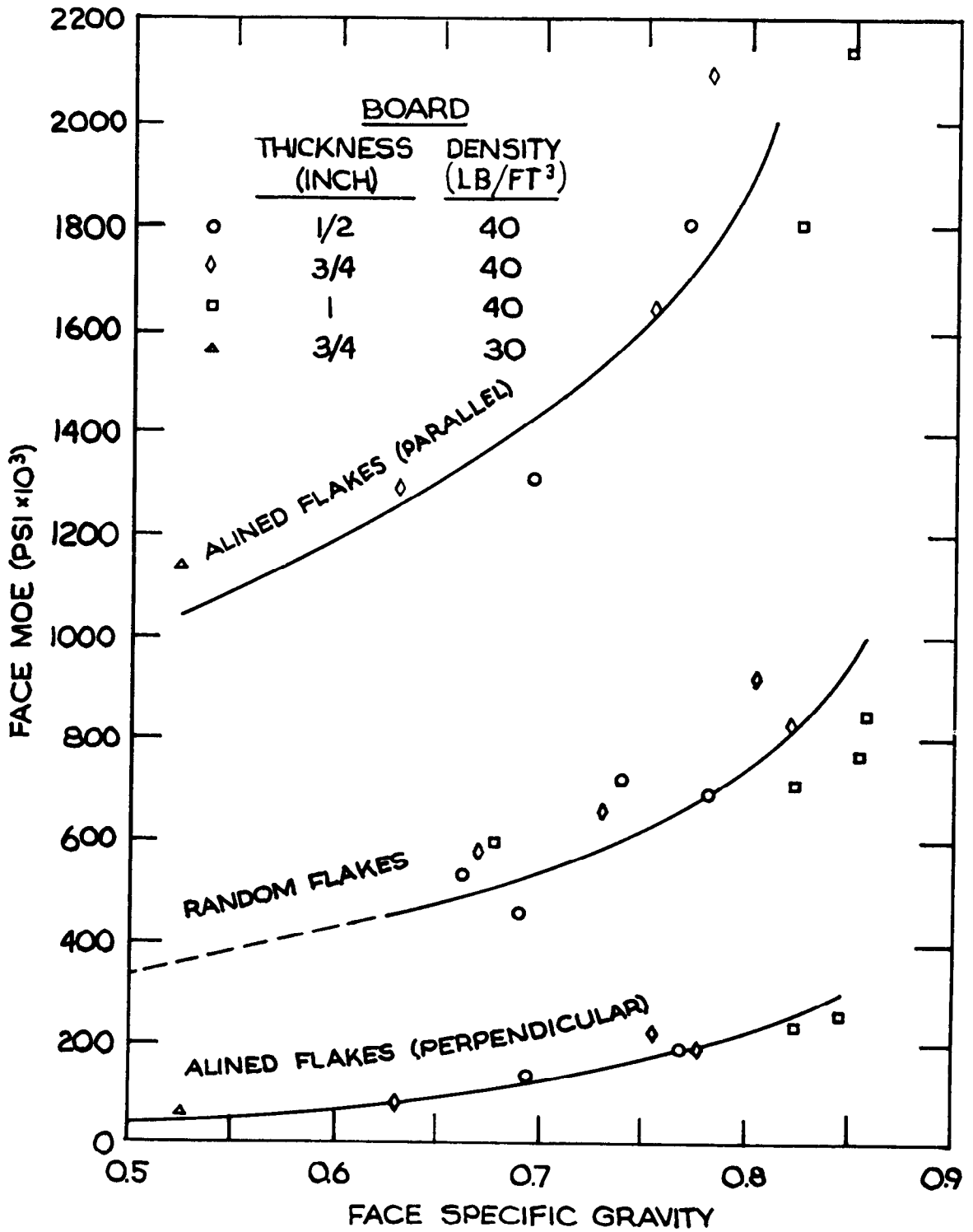


Figure 13.--Relationship between specific gravity and modulus of elasticity of particleboard face layers.
 (From Geimer et al 1975)

(M 144 413)

random cores.

The particleboard literature appears to lack high-quality information pertaining to processing variables and their effect on MOE. This is not surprising in that applications of particleboard have, in the past, been more concerned with the ultimate strength and not the board's stiffness. However, with increasing interest in structural applications, additional work is necessary to consistently attain the high MOE required in such applications. The work of Geimer *et al.* (1975) has shown the influence of surface density on the effective MOE and future researchers should not simply determine MOE values as a function of average board density, but should also measure the vertical density gradient.

Internal Bond

The internal bond (IB), or tensile strength perpendicular to the board surface, is a widely determined property in all particleboard research. A particleboard with a well-cured adhesive will normally fail when stressed in tension perpendicular to the board surface, near the midpoint of the thickness. This is the lowest density region in a hot-pressed panel particleboard and consolidation of the mat to obtain intimate particle-particle contact is lowest in this region. Most researchers have found higher IB values with increasing board density, increasing resin content, and increasing press time and temperature. Consequently, this portion of this review will be restricted to studies concerned with the effect on internal bond of particle geometry and related parameters.

The normal vertical density gradient in flat-pressed particleboard adversely affects the IB. Highly densified surfaces increase the bending strength of particleboard, as shown by Geimer *et al.* (1975), but the resultant lower density core region normally reduces the IB (Strickler 1959; Plath and Schnitzler 1974). However, Strickler (1959) and Geimer *et al.* (1975) did not find a strong correlation between core density and internal bond; Strickler attributed this to moisture and press cycle effects.

Kehr *et al.* (1964) found a sharp decrease in the IB as the resin output per spray nozzle was increased above 100 gm/min. The large adhesive droplets did not result in as good blending as obtained with small adhesives droplets (see "Physical Properties").

Excessive moisture in the particleboard mat will migrate to the core during hot pressing and interfere with the chemical reaction neces-

sary to cure the resin (Lehmann 1960; Hart and Rice 1963; Gatchell *et al.* 1966; Heebink *et al.* 1972). Roffael *et al.* (1972) increased the core temperature to 220° C and obtained improved internal bonds, since at this temperature most of the water is removed and does not interfere with the adhesive curing.

Vital *et al.* did not find a close relationship between IB and board density for particleboards made from mixtures of four exotic hardwoods. They reported a decrease in IB at constant board density as the compaction ratio increased from 1.2 to 1.6. The IB decrease was attributed to the increased amount of flake damage at the high compaction. In contrast, Hse (1975) found increasing internal bonds with increasing compaction ratio at all compaction ratios studied between 0.9 and 1.5 with 3-inch-long flakes from nine hardwood species. The larger flakes (Hse 1975) responded to the higher compaction by appearing to better utilize the 4 percent phenolic adhesive, while the shorter and generally lower density flakes (Vital *et al.* 1974) did not require the high pressure for good bonding and appeared to be weakened at the higher compaction ratio.

Maloney (1975), in his study of short retention-time blenders, reported decreased IB values at board specific gravities above 0.75 for a 6 percent level of phenol-formaldehyde adhesive (resin solids on OD wood) with flakes blended in a laboratory rotary blender. Generally, Maloney's (1975) results show a direct linear relationship between IB and board specific gravity with a phenol-formaldehyde adhesive content of 2 percent, but even at the high specific gravity, IB was below 100 lb/in.² At 4 and 6 percent resin, the IB increased with board specific gravity but at a decreasing rate, except for the instance mentioned above where the IB decreased.

The internal bond strength improves as the core particle configuration changes from a long wide flake to planer shavings or slivers (Childs 1956; Talbott and Maloney 1957; Suchsland 1959; Brumbaugh 1960; Rackwitz 1963; Kimoto *et al.* 1964; Gatchell *et al.* 1966; Stewart and Lehmann 1973; Lehmann 1974) as shown in the "Bending Strength" in this report, the reverse is true for modulus of rupture and modulus of elasticity--i.e., large flakes improve these properties. Consequently, in making a homogeneous particleboard, the manufacturer must reach a compromise on which particle configuration to use to meet the projected application demands. A three-layer particleboard construction, with coarse particles in the core and flakes at the surface, is

often used to optimize both properties in the same board (Keylwerth 1958; Suchsland 1960).

Talbott and Maloney (1957) reported a significant improvement in internal bond for all board specific gravities, particle sizes, and phenol-formaldehyde resin contents when 0.75 percent wax was added to the furnish. Hann *et al.* (1962) also reported increased IB values when 1 percent wax was added to particleboard bonded with 4 percent urea-formaldehyde adhesive. Heebink and Hann (1959) found no improvement in strength with addition of 1 percent wax to a board with 8 percent urea-formaldehyde adhesive. Gatchell *et al.* (1966) found a wax content above 2 percent interfered with inter-particle bonding. Stegmann and Durst (1965) also found reduced strength with increasing wax content. Wax addition to particleboard improves the liquid water resistance but it is extremely doubtful that it would also improve the internal bond, as has been reported, since there is no strong chemical attraction between wax and wood particles sufficient to improve the interparticle bonding. Excessive wax addition will hinder bond formation.

Other Strength Properties

The lack of additional mechanical tests in the particleboard literature is surprising, especially when the standards for conducting these tests appear in the ASTM Standard Method D 1037. Very few reports appear in which shear strength in the plane of the board and tensile and compressive strengths parallel to the surface have been determined, and the number of reports concerned with screw withdrawal is not much greater. The addition of interlaminar shear and edgewise shear only recently to the ASTM Standard Method accounts for the lack of this data. The other properties have appeared in the Methods for a number of years.

McNatt (1973) has evaluated nine commercially produced particleboards for basic engineering properties in an attempt to eventually establish design stresses for particleboard. The boards selected represented a range of thicknesses, resin types, particle configurations and wood species, as well as layered and homogeneous structures. Interlaminar shear strength and internal bond were positively and linearly correlated for all particleboards. This is not surprising, as both are a measure of the interparticle bonding in the core. A positive and linear correlation between modulus of elasticity in bending and plate shear modulus was also obtained for all boards. Tensile strength parallel to the surface was linearly and positively correlated to the modulus of rupture and the logarithm of tensile

strength parallel to the surface was correlated to the edgewise shear strength. The latter regression was significantly improved by removing the data for a board with large aspen flakes which had a phenol-formaldehyde adhesive and was intended for structural applications. The large component flakes of this material resulted in greater variability in the overall properties as compared to boards made with smaller particles. Another significant finding (McNatt 1973) was a lack of any large consistent differences in properties due to orientation of test specimens either parallel or perpendicular to the mat forming direction. This report by McNatt (1973) begins to fill a large void in the literature and it is hoped other researchers will follow his example.

In a related study, McNatt (1974) determined the effect of various relative humidity conditions on the same engineering properties determined earlier (McNatt 1973). Five commercial particleboards were tested at 65 percent relative humidity to establish the control level followed by repeated testing after further relative humidity exposures of various time periods. No significant differences were noted in the response to relative humidity changes for the different boards, they all behaved substantially the same regardless of resin type, species, or density. All properties increased above 80 percent, whereas the bending, tension, and shear properties decreased, and the compressive properties increased at overdry conditions. At 30 percent relative humidity all properties, except bending strength, were higher than the controls were at 65 percent relative humidity.

Superfesky (1974), in a study to compare two different sheet metal screws for the screw withdrawal resistance test in particleboard, found edge withdrawal lower than face withdrawal for the eight particleboards tested. No relationship was found between density and screw withdrawal resistance of these commercial boards because board structure, particle size, resin type, species, and processing varied between boards. Post (1961) reported only a weak relationship between screw withdrawal resistance and resin content. Flake size, unless excessively thick, also had only a small effect.

Didriksson *et al.* (1974) have reported on the edge-splitting tendency of wood-based materials, including particleboard. Their technique consisted of measuring the internal bond both before and after placing a screw into the sample edge. In general, the IB was approximately 10 percent lower with the screw inserted at the thickness midpoint in the board edge. Carroll (1970) has shown the importance

of not overdriving a screw in particleboard; overdriving substantially reduces screw withdrawal strength. Carroll suggested this drastic reduction in screw withdrawal resistance as a result of overdriving may contribute to particleboard's poor reputation for fastening with screws.

Johnson and Haygreen (1974) have measured the impact strength, with a sandbag drop test, of four particleboard types and compared them to plywood. The impact strength of particleboard was well-correlated to the toughness, but only moderately and negatively correlated to board density and torsional internal bond. No correlation existed between impact strength and static bending properties.

Relatively little literature is available on the rheological behavior of particleboard. The creep of particleboard subjected to long term static loads under cyclic relative humidity conditions will become extremely important as the structural use of particleboard increases. Norimoto and Yamada (1966) found particleboard possessed significantly more creep than did solid wood. Bryan (1960) published one of the first articles which appeared in this country on the long term loading behavior of particleboard. He measured the time to failure for boards loaded to various percentages of their maximum load and reported that adhesive type and density were not significant factors. The correlation coefficients for a linear relationship between the flexural stress ratio and the logarithm of time were variable and not highly significant.

Bryan and Schniewind (1965) studied the effect of cyclic moisture conditions on the creep properties of both urea-formaldehyde and phenol-formaldehyde bonded particle boards and reported increases in creep when the moisture content of the specimen changed. Adsorption (from 6 to 8 percent MC) resulted in higher creep levels in all cases but desorption for high initial moisture contents (from 18 to 6 percent MC) did not increase creep; desorption from intermediate moisture contents (from 12 to 6 percent MC) exhibited creep values similar to adsorption. Bryan and Schniewind (1965) also presented data showing creep in particleboard to be more severe under cyclic relative humidity conditions and to show only very little recovery when the relative humidity decreases from 50 to 30 percent. Here also, no significant differences between urea-formaldehyde and phenol-formaldehyde bonded boards were noted.

Many further studies are presently being conducted on the creep and impact strength of particleboard. Not only are these properties not adequately known for particleboard but the effects of processing factors on these properties are also unknown. However, no information is available specifying impact strength and creep resistance required for a material to be applicable for construction purposes. When this is determined, work can proceed on designing a particleboard product to meet these requirements, if presently available particleboard is unsatisfactory.

MOISTURE AND DIMENSIONAL PROPERTIES

Particleboard is hygroscopic and dimensionally unstable when exposed to water vapor or liquid water. Because the material possesses hygroscopic properties similar to solid wood, it will adsorb moisture from high humidity atmosphere and increase in volume; however, subsequent drying does not result in a return to the original volume. Excessive dimensional changes in the material after installation can be disastrous; proper installation and efforts to eliminate large moisture fluctuations are mandatory for satisfactory utilization of particleboard. This irreversible, dimensional instability of particleboard is believed to be the result of compressive stresses incorporated into the panel in the pressing operation, and of possible hydrolysis of the urea-formaldehyde adhesives at elevated moisture conditions. The release of compressive stresses, called spring-

back, has been reviewed earlier; this section will review moisture content changes and dimensional properties as affected by board density, particle configuration, adhesives, and wax content.

Equilibrium Moisture Content

Relatively little literature is available in which the effect of particleboard processing on the equilibrium moisture content (EMC) for various relative humidities has been studied. Halligan and Schniewind (1972) presented sorption isotherms for two particleboards of different densities and different urea-formaldehyde adhesive levels. A 50 lb/ft³ board with 10 percent adhesive content (resin solids on OD wood) had lower equilibrium moisture contents at all relative humidities than did boards of 37 lb/ft³ with a 4 and 6 percent adhe-

sive content in the core and surface layers, respectively (fig. 14). Below 30 percent relative humidity, the isotherm for the 50 lb/ft³ board was slightly below the isotherm for solid wood. Above 30 percent relative humidity, the increase in moisture content with increasing relative humidity was slower for both particleboards when compared to solid wood. At the higher relative humidities, the solid wood attained an EMC at least 5 percent above that of either particleboard.

From the tabulated data presented (Halligan and Schniewind 1972), board density was the most significant factor in reducing EMC; as density increased within each resin level, EMC decreased. Only at relative humidities above 90 percent was the EMC consistently reduced as the resin content increased. However, the increased bonding efficiency believed to occur as the board density increased may have spread the adhesive sufficiently to block addi-

tional sorption sites. The resulting reduced sorption would appear to have been due to higher density but may, in fact, have been due to the adhesive. No mention of this possibility was given by Halligan and Schniewind nor can this hypothesis be tested on their data. Higher amounts of wood material should not reduce the EMC as the hygroscopicity of the additional wood is the same, but the additional press time required for the higher density board may have reduced the hygroscopicity of the wood.

No good comparison between the equilibrium moisture content of urea-formaldehyde and phenol-formaldehyde-bonded boards is possible from the work of Halligan and Schniewind (1972) because the adhesive and wax contents were not equal. Steam-treated phenol-bonded boards of 37 lb/ft³ appeared to have lower EMC values, at relative humidities above 50 percent, than the untreated boards.

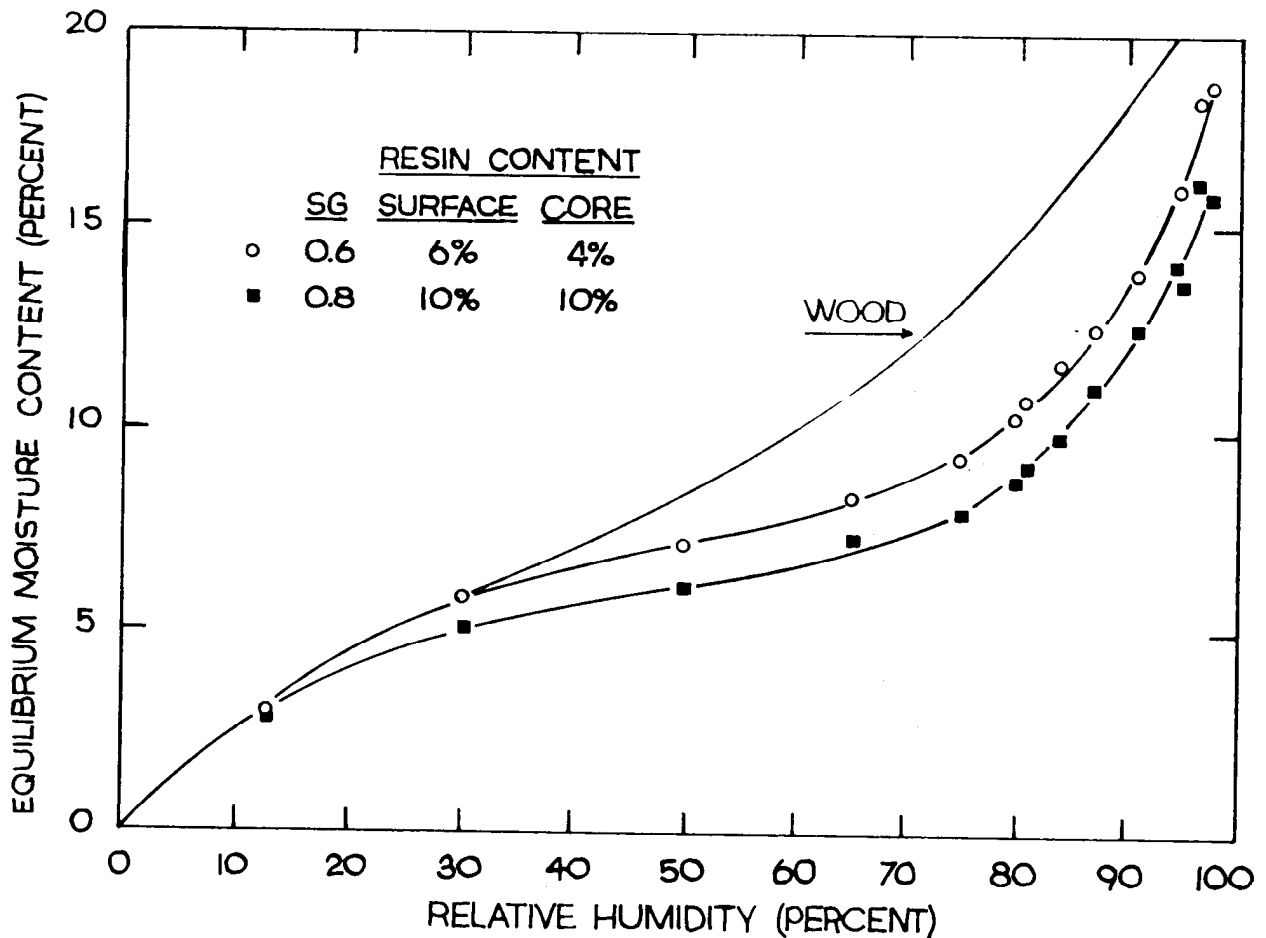


Figure 14.--Absorption isotherms for particleboards compared to wood, at 70° F.

(From Halligan and Schniewind 1972)

(M 144 414)

However, the treated 44 lb/ft³ board had lower equilibrium moisture contents at only 5 of the 12 relative humidities studied. The results do not entirely confirm the author's statement that steam treatment lowered the EMC values.

Suchsland (1972) determined adsorption and desorption isotherms for ten commercial particleboards of both interior and exterior types. All boards exhibited large sorption hysteresis, and isotherms were lower than those of solid wood, but the interior boards (assumed to be urea-formaldehyde bonded) always possessed a higher moisture content at a given relative humidity than did the exterior particleboards (assumed to be phenol-formaldehyde bonded). Suchsland theorized that exposure to high temperatures commonly encountered in drying was responsible for the reduced hygroscopicity of particleboard as compared to solid wood. He also pointed out that press temperatures for the exterior particleboards are higher than those used for interior particleboard, possibly accounting for the lower hygroscopicity of the exterior boards.

Jorgensen and Odell (1961) found that particleboards with intermediate adhesive spread levels (6.54 gm resin solids/m² of particle surface) reached a lower EMC than did the particleboard with either a lower or higher adhesive spread level (3.27 and 13.07 gm resin solids/m² of particle surface). Jorgensen and Odell (1961) could not explain this behavior and the lack of further research in this area does not allow confirmation of these findings.

Schneider (1973) reported extremely high EMC values for phenol-formaldehyde-bonded particleboard at relative humidities above 90 percent. At relative humidities below 90 percent, the EMC values were not significantly higher than solid wood. Urea-formaldehyde-bonded particleboard had isotherms similar to those of wood below 60 percent relative humidity but above this level the EMC was below that of wood.

Thermal treatments to which particleboards are subjected in the hot press are believed to reduce the sorption ability of the wood (Seifert 1972; Wittmann 1973). Seifert found heat treatment to be much more effective in reducing adsorption at low relative humidities; he reported that capillary condensation at high relative humidities is less affected by thermal treatments. Seifert also found that reduction of sorption caused by non-hygroscopic adhesives blocking the sorption sites does not occur.

There appears to be no consistent pattern in the literature for the effect of various pro-

cessing parameters on the equilibrium moisture content of particleboard. Very little information has been published in this area. The lack of this fundamental knowledge has not restricted the use of particleboard and, as there are many other problems which need more urgent attention, research in this area should not be given top priority.

It is obvious that particleboard--directly derived from the hygroscopic material, wood--will also adsorb and release moisture when subjected to high and low relative humidities. The exact equilibrium moisture content attained by a particular particleboard at a given relative humidity is of much less importance than are the dimensional changes which occur as the moisture content fluctuates. These dimensional changes have been widely studied and are reviewed in the following section.

Dimensional Properties

Solid wood shrinks and swells when subjected to environmental conditions causing desorption or adsorption of water. Particleboard also shrinks and swells under the same conditions, but the magnitude of this dimensional change is much greater in the thickness direction of conventionally flat-pressed particleboard than would be expected from the normal shrinking and swelling of wood material. The linear dimensional changes in particleboard are normally slightly greater than the longitudinal changes found in solid wood.

Kollman *et al.* (1975) graphically compared the dimensional stability of particleboard to that of solid pine wood. The average linear expansion compares favorably with the longitudinal swelling of pine, but the thickness swelling is much greater than the tangential swelling and continues to increase at an increasing rate with moisture content. This reflects the large amount of springback associated with flat-pressed particleboard as a result of the compressive set during manufacture.

The abnormal thickness swelling observed in flat-pressed board subjected to high humidities is not entirely reversible when the board is subsequently redried. This irreversible thickness swelling is the springback discussed earlier and results from the compressive stresses which are "set" in the board during hot pressing. Plasticization by moisture releases this set and, in some instances, the springback can be sufficiently large to destroy a major portion of the interparticle bonding.

The dimensional changes of particleboard subjected to various relative humidities have been widely studied, but direct comparison

between reports is often difficult due to the enormous number of processing variables which directly and indirectly affect dimensional changes. In addition, there are basically two methods which are used to study these changes: ASTM Standard Method D 1037 (ASTM 1975) and the vacuum-pressure-soak (VPS) method first reported in the particleboard literature by Heebink (1967).

The ASTM Method D 1037 for thickness swell requires moisture conditioning to a constant weight, then submersion of the specimen in water with no pressure. Thickness measurements are made after 2 and 24 hours submersion and dimension changes are expressed as a percent of the original thickness. Linear dimensional changes are determined from another specimen conditioned to 90 percent relative humidity at 20° C after the sample has been initially conditioned to 50 percent relative humidity. Linear expansion is then expressed as a percent increase per inch of the original dimension. Initial humidity levels other than 50 percent are often used; 30 to 90 percent is a frequently used relative humidity exposure test.

The VPS method uses matched samples of particleboard--one sample oven-dried, the other subjected to 30 minutes of vacuum followed by 22 hours submerged in water under static pressure. The linear dimensional changes for the two specimens are added together and expressed as a percent change per inch of the original dimension. The thickness change is calculated from the soaked specimen as a percent of the oven-dry thickness.

The advantage of the vacuum-pressure-soak method is that prior conditioning of the specimens to a constant weight is not necessary as all dimensional changes are based upon the oven-dry dimensions. This reduces the time required to obtain the information, but the ASTM method, with the conditioning step prior to testing, should allow the moisture gradients induced in the boards during hot pressing to be substantially eliminated. The effect, if any, of this moisture content gradient on the dimensional properties of particleboard is not known.

Water Absorption and Thickness Swelling

Water absorption and thickness swelling normally are determined on the same specimen in both the ASTM and VPS methods. The ASTM method specifies horizontal submersion of a 12- X 12-inch specimen and notes vertical submersion will result in absorption of more water; therefore, comparisons between water absorption and thickness swelling

results obtained by the two techniques is not possible. The specimen size used in the ASTM test by various researchers is variable, limiting direct comparisons.

Johnson (1964) studied 24-hour water soaking in both vertical and horizontal positions of 26 commercial particleboard specimens, 3 X 15 inches. In general, more water was absorbed by the vertically soaked specimens, although five of the 26 particleboards absorbed more water in the horizontal position. The vertically soaked samples absorbed the moisture more quickly than did the horizontally soaked samples, but at an equal moisture content increase there was very little difference in the thickness swelling. However, because the vertically soaked specimen absorbed more water and absorbed it faster, it also had more thickness swelling at any given soaking time.

Johnson (1964) also measured the moisture content and thickness swelling of boards conditioned at 65 percent relative humidity and 70° F for 44 days (fig. 15). These samples were initially conditioned for one month at 30 percent relative humidity at 90° F. The thickness swelling at 65 percent relative humidity was less than 2 percent and the moisture content increase was approximately 2.5 percent. The data indicate that samples attained a constant EMC and thickness swelling during the 154 days at this humidity. However, the data for the 90 percent humidity condition definitely showed thickness swelling still increasing rapidly at the end of the 44-day period. Thickness swelling versus moisture content was approximately linear between 2 and 14 days at this condition. After 14 days the moisture content increased less than one percent for the remaining 30 days at this relative humidity but the thickness swelling increased more than 3 percent and was still increasing when the test was terminated. This indicates that a relaxation or other time-dependent phenomenon such as springback, independent of moisture content, is controlling the thickness swelling. The author made no comment on this behavior.

The processing parameters and their effect on water absorption and thickness swelling cannot be studied from Johnson's paper; no identification or description was given other than the particleboard thicknesses. Johnson's paper does illustrate the long time period required to attain equilibrium thickness swelling data at various relative humidities. The literature appears to contain much swelling data which has been obtained under non-equilibrium conditions as a result

of short conditioning periods (Neusser *et al.* 1965).

Density.--The effect of board density on the thickness swelling of particleboard is confounded with the springback behavior. Higher density boards will possess more compressive set than lower density boards when both are made with the same wood furnish.

Therefore, it is not surprising that thickness swelling is normally reported to increase with increasing board density (for example, Gatchell *et al.* 1966; Halligan and Schniewind 1972; Hse 1975). However, this finding has not been unanimous; other authors have found either an increase or no change in thickness stability with increasing particleboard density

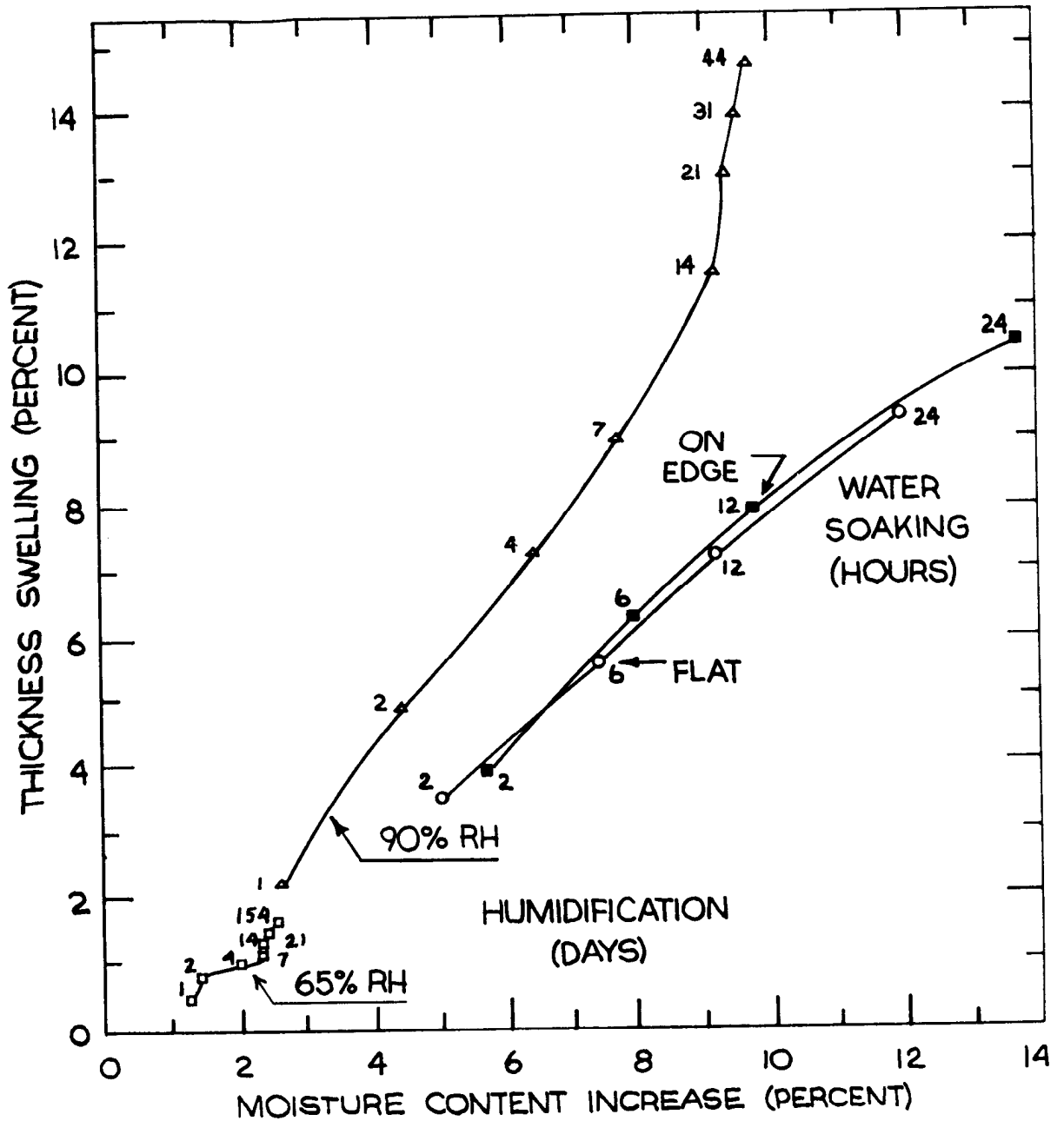


Figure 15.--Relationship between thickness swelling and moisture content increase.

(From Johnson 1964)

(M 144 415)

(Lehmann and Hefty 1973; Vital *et al.* 1974)

Vital *et al.* (1974), with particleboards from exotic hardwoods of four different wood densities, studied the water absorption and thickness swelling properties. Two compaction ratios were used and boards were made with all possible species mixtures of one, two, three, and four species. Water absorption and thickness swelling values were determined for all boards over the relative humidity increments of 30 to 90 percent, 50 to 90 percent, and 30 percent to water soaking for 24 hours. Unfortunately, the specimen sizes used are not reported, nor is the conditioning time at each relative humidity given in the paper. Since the highest density board was 0.93 gm/cm^3 (grams per cubic centimeter) (OD weight, volume at 65 percent relative humidity) the time to equilibrium moisture content can be assumed to have been quite long.

Not surprisingly, the water absorption in the 24-hour water soak test was highly correlated with the board density (Vital *et al.* 1974). For all species combinations, the higher compaction ratio (1.6) always absorbed a lower amount of water than the lower compaction ratio (1.2). Water entry into the higher density boards occurred at a slower rate due to the decreased porosity and the increased wood material. Total water absorbed from the atmosphere (30 to 90 and 50 to 90 percent relative humidity increments) was also higher in the lower compaction boards in all cases, but the difference between the two ratios was much less significant (approximately 1 percent moisture content). The longer times at these relative humidities obviously allowed the moisture to equalize much more uniformly through the board than was possible in the 24-hour water soak.

With only a few exceptions, an increase in board density resulted in a decrease in thickness swelling for all three exposure conditions. The lower moisture absorbed by the higher density boards was one possible explanation for this behavior. Additional reasons given were the increased interparticle bonding at the higher density or the higher moisture content during pressing, as reduced porosity of the high-density mat limits the escape of moisture and allows increased compressive set in the final panel.

Lehmann and Hefty (1973) found no relationship between particleboard density and thickness swelling except at the 2 percent adhesive level. At this level of urea-formaldehyde resin, the lower density board, 0.65 gm/cm^3 (OD weight, volume at 65 percent relative humidity), had lower thickness swell-

ing than the board with a density of 0.75 gm/cm^3 (OD weight volume at 65 percent relative humidity).

Gatchell *et al.* (1966) determined the thickness swelling of phenolic bonded particleboard specimens. 22 inches long, 5/8 inch wide, and of various densities. The exposure conditions for determining the thickness swelling were from oven-dry to 30, 65, 80, and 90 percent relative humidity, as well as a 30-day water soak period. Thickness swelling was independent of density up to 80 percent relative humidity for densities of 30, 40, and 50 lb/ft^3 . Above 80 percent the high-density particleboard had higher thickness swelling, attributed to springback from the higher compressive set at this density. Lehmann (1970) also found no significant effect of density on the thickness swelling of Douglas-fir particleboard between 30 and 90 percent relative humidity.

Roffael and Rauch (1972a) reported on the thickness swelling of particleboards with a wide range of densities (0.51 to 0.94 gm/cm^3) when subjected to water soaking at 20° C . They found a decrease in absorption but an increase in thickness swelling as the density increased. The ratio of thickness swelling to water absorption at low board densities was constant for practically the entire 10-day soaking period. For the high-density boards, this ratio increased to a maximum with increasing soaking time followed by a decrease in the longer soaking times. This behavior reflects the slow rate of thickness swelling found for the boards with densities above 0.7 gm/cm^3 (fig.16) and is attributed to low diffusion rates in the high-density boards. However, the reduced porosity in the high-density boards, as compared to those of lower density, prevented rapid liquid water penetration throughout the board; consequently, the diffusion path of the water into individual component particles was much longer and the subsequent rate of thickness swelling was reduced in the high-density material.

Halligan and Schniewind (1972), for a series of particleboards with three resin contents at each of three densities, found a higher thickness swelling as the board density increased for moisture contents above 10 percent. Below 10 percent moisture content, board density appeared to have little influence on thickness swelling. The boards reached 10 percent moisture content at approximately 80 percent relative humidity; therefore, the data agree well with that of Gatchell *et al.* (1966).

Stewart and Lehmann (1973) did not find a consistent relationship between thickness

swelling and board density for particleboards produced from cross-grain, knife-planed flakes from four different hardwoods. Basswood particles produced particleboard in which thickness swelling decreased significantly as board density increased. Yellow poplar, red oak, and hickory all had approximately the same thickness swelling regardless of particleboard density.

Hann *et al.* (1992) reported increased thickness swelling in 24-hour water soaking when the density of Douglas-fir particleboard was increased from 34 to 43 lb/ft³. This was true for both urea-formaldehyde- and phenol-formaldehyde-bonded boards.

Suchsland (1973) determined the thickness swelling of ten commercial particleboards under cyclic relative humidity and water soak exposure and found no correlation between board density and thickness swelling. The rate of thickness swelling was initially less than the rate of water volume absorption which, according to Suchsland, indicates internal swelling. As the moisture content increased, the rate of swelling was higher than the rate of water volume absorption and was attributed to internal failures in the lower density core. Suchsland stated that efforts to reduce thickness swelling should concentrate on reducing the horizontal density distribution

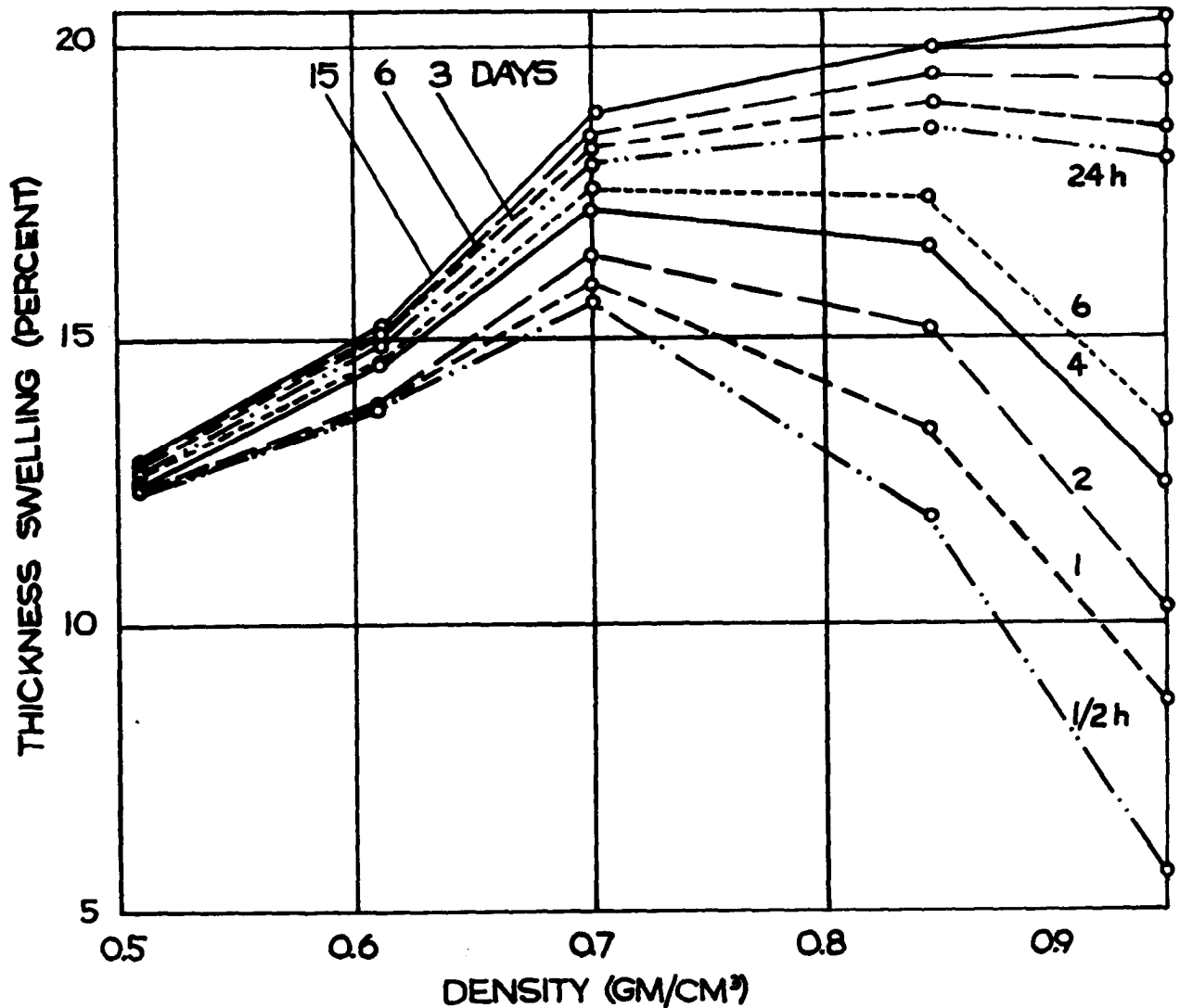


Figure 16.--Influence of particleboard density on rate of thickness swelling.

(From Roffael and Rauch 1972a)

(M 144 416)

so that high- and low-density regions are eliminated. This ideal can never be obtained with wood particles but it can be approached as the particle size decreases.

Lehmann (1974) found a relatively minor effect of density on thickness swelling with 1- and 30-day water soaking. The results were obtained with Douglas-fir particleboard made at two densities (37.5 and 42.5 lb/ft³, OD weight and volume at 65 percent relative humidity) with various flake configurations and three levels of phenol-formaldehyde adhesive content. The higher density board exhibited less swelling and water absorption with the 24-hour soak but more swelling in the 30-day soak and in the OD-VPS test than the lower density board. This is to be expected because the slower diffusion rate in the higher density material prevents attainment of moisture equilibrium in the 24-hour soak. However, no statistically significant effect was found relating particleboard density to the thickness swelling in this study.

Hse (1975), in contrast to Lehmann (1974), found increased thickness swelling with increased board density in the 5-hour boil and the VPS tests for phenol-formaldehyde-bonded particleboard. However, in the 50 to 90 percent relative humidity tests no density effect was obtained. Gertjeansen *et al.* (1973) found increased thickness swelling with increased board density for phenolic-bonded wafer-type particleboard made with various mixtures of aspen, tamarack, and paper birch. They used the VPS test for determining thickness swelling.

A consistent relationship between board density and thickness swelling is not obvious in the present literature. Reports of increased thickness swelling with increasing board density are balanced by other reports in which no relationship is evident. In most instances in which thickness swelling was reported to be related to board density, the test method employed was the VPS test or a boiling water test. These two methods and--to a slightly lesser degree--the 24-hour water soak will allow faster compressive stress release than will methods in which the boards are conditioned at various relative humidities. Also, moisture equilibrium at a given relative humidity does not imply thickness swelling equilibrium, especially at higher relative humidities. Compressive stress release, resulting in additional thickness swelling, can probably continue to occur long after moisture equilibrium is attained. Higher density boards are subjected to higher compressive failure during production; therefore, more springback would be expected from these boards when re-wetted. In appli-

cations such as furniture corestock, in which exposure to liquid water is minimal, the thickness swelling determined with various relative humidity exposures appears to be more applicable. The long exposure times required for this test severely limit its use by most researchers.

Particle configuration.--The effect of particle size and shape on the thickness swelling of particleboard has been widely reported in the literature. Turner (1954) was one of the first investigators to systematically study this variable. His test method consisted of determining the thickness after two water-soaking-ovendrying cycles and expressing this thickness as a percent of the original thickness. This procedure is more severe than the presently used 24-hour water soak. Turner (1954) showed that flake length has no significant effect upon thickness swelling. Long, thin, narrow strands with 2 percent phenolic resin resulted in a poorer thickness stability than the flat flakes, but, with increased resin contents of 4 and 8 percent, the stability of the board produced with the strands was better than the flakes at equal resin content (resin solids on OD wood).

Lehmann (1974), in his study of Douglas-fir flakes 0.5, 1.0, and 2.0 inches long and 0.030 and 0.045 inch thick, found no significant effect of flake length on particleboard thickness swelling with either the VPS or relative humidity exposure tests. However, the thinner flakes resulted in slightly less thickness swelling, especially in the OD-VPS test. Brumbaugh (1960) also reported improved thickness stability with thin (0.009 inch) Douglas-fir flakes and a decrease in thickness stability with a flake length of 0.5 inch. The water absorption of the OS-inch-long flake was significantly higher, reflecting the increased percentage of end-grain on the flake surface. Longer flakes (1, 2, and 4 inches) produced a more stable board as determined by the 24-hour water soak test. Jorgensen and Odell (1961) and Post (1956) also found improved thickness stability in particleboard produced with oak flakes 0.006 inch thick as compared to the other flake thicknesses studied (0.012, 0.025, and 0.050 inch). The flake length used in this study (0.5, 1, 2, and 4 inches) did not significantly affect the thickness stability.

Stewart and Lehmann (1973), using cross-grain, knife-planed hardwood flakes of four species and three thicknesses (0.006, 0.012, and 0.016 inch), found no relationship between the flake thickness and thickness swelling in the resulting particleboard. Kimoto *et al.* (1964) reported a slight decrease in thickness swelling, determined by the water soak test,

as the particle dimensions increased for low-density lauan particleboard. No effect of particle configuration on thickness stability was evident in the relative humidity exposure test.

Heebink and Hann (1959) found northern red oak flakes 1 inch long produced a more stable particleboard than did flakes 0.25 inch long. Post (1961) reported that flake length had no relationship to thickness stability when the flake thickness was below 0.012 inch. With flakes thicker than that, stability was improved with increasing flake length.

Beech (1975) studied the thickness swelling properties of phenol-formaldehyde-bonded particleboard made with angle-cut particles of Scots pine. The angle-cut flakes were produced in such a manner that the orientation of the grain was approximately 20° out of the flake plane. This allowed a portion of the large dimensional movement across the grain to be shifted to the linear dimensional movement in the produced particleboard and further allowed the wood longitudinal direction to be slightly oriented in the board thickness. This reduced the thickness swelling for particleboards produced for these angle-cut particles below the level obtained in particleboard produced with standard particles. However, as would be expected, this particle also resulted in boards with substantially reduced strength. Beech (1975) did not determine linear expansion but this, too, would be expected to increase with the angle-cut particles. The use of angle-cut particles as a method for reducing the thickness swelling in particleboard appears to have limited potential.

The available literature appears to be practically unanimous in that better thickness stability is obtained with boards produced from thin particles than from thick particles. The lower wood mass in each particle and the increased number of particle-particle interfaces possibly allows better dispersion of the hygroscopic swelling into the interparticle voids. Consequently, this swelling into the macroscopic board voids, not internal swelling within the wood particles, results in less thickness swelling.

Much less agreement is found regarding the influence of particle length on thickness swelling. In general, it appears that increasing particle length improves the thickness stability. A possible reason for this may be as the particle length increases and the particle is bonded to a larger region of the board, it is more effective in dispersing localized swelling stresses over a larger region--i.e., it serves as a moderating influence and reduces the effect

of high density regions on thickness swelling. Further research is required on both the macrostructure and microstructure of particleboard before the true influence of particle length on the thickness swelling of particleboard is known.

Resin and wax.--Increasing the resin content improves the thickness stability of particleboard (Hann *et al.* 1963; Kimoto *et al.* 1964; Gatchell *et al.* 1966; Lehmann and Hefty 1973). Lehmann (1970) found optimum thickness swelling for urea-formaldehyde-bonded Douglas-fir particleboard occurred below 8 percent adhesive (resin solids on OD wood). Lehmann (1974) also found improved thickness stability in Douglas-fir flakeboard with increasing levels of phenol-formaldehyde adhesive. The three adhesive levels studied (3, 6, and 9 percent resin solids on OD wood) did not indicate an optimum level, but the improvement obtained between 6 and 9 percent was lower than the improvement between 3 and 6 percent. Beech (1975) reported reduced irreversible swelling or springback when the phenol-formaldehyde adhesive content was increased from 9 to 12 percent. He also found less reversible and irreversible swelling for Scots pine and beech particleboard subjected to a 24-hour water soak when bonded with phenol-formaldehyde instead of urea-formaldehyde adhesive. Oak particleboard bonded with urea-formaldehyde was more stable than when phenol-formaldehyde was the binder. This was attributed to the interference of the acidic extracts on the alkaline catalyst in the phenol-formaldehyde adhesive.

Increasing the resin content in a given particleboard will result in improved interparticle bonding which should also improve the thickness stability. However, in all probability there is a level at which additional resin will no longer enhance this bonding and serves only to impregnate or coat the component particles. This is the basis upon which impregnating resins have been used to limit the hygroscopicity of the material, but the economics do not presently justify this treatment.

The use of a paraffin wax is widespread in the particleboard industry for both urea-formaldehyde- and phenol-formaldehyde-bonded boards. Contradictory claims appear in the literature as to the value of the wax in reducing the dimensional changes of particleboard. Gatchell *et al.* (1966) and Heebink and Hann (1959) found no reduction in either moisture content or dimensional changes for wax-treated particleboard under long-term exposure to water vapor. Stegmann and Durst (1965) reported a large reduction in both water

absorption and thickness swelling in the 24-hour water soak test by addition of wax. However, other researchers (Maku *et al.* 1956, 1957; Heebink and Hann 1959) indicate wax addition moderates dimensional changes during fluctuations in relative humidity and short-term exposures to liquid water. Excessive amounts of wax, greater than 1 percent wax solids on oven-dry wood, interferes with adhesive bonding and reduces the strength properties.

Other proposals which have been made to reduce the hygroscopicity and consequently improve the dimensional stability of particleboard are heating the unbonded particles or the finished particleboards with or without steam (Suchsland and Enlow 1968; Heebink and Hefty 1969; Halligan and Schniewind 1972; Burmester 1973; Hujanen 1973). Post-steaming appears to be the most effective method for improving dimensional stability but the additional costs of this treatment have prevented its acceptance by the industry.

Linear Expansion

The linear expansion of particleboard when exposed to moisture is much less than the radial swelling, but greater than the longitudinal swelling, of solid wood. Considering the orientation of the component particles in the mat, this response is not surprising. Most particles are oriented with grain parallel to the plane of the particleboard. In a randomly formed board, particles are deposited at all possible angles to each other but still with the grain direction basically in the plane of the board. Consequently, the linear expansion in the x and y directions will be equal to each other but greater than the longitudinal swelling and less than the transverse swelling of solid wood. In oriented-flake particleboards, in which the individual particles are aligned parallel to one another in the panel, the linear expansion in the two directions of the panel will not be equal (Geimer *et al.* 1975). The linear expansion in the direction of orientation will decrease and approach the longitudinal swelling of the solid wood while the linear expansion perpendicular to the alignment will increase and approach the transverse swelling of solid wood. With increased usage of aligned particleboard in the construction industry, the isotropic swelling behavior of this material will have to be recognized and installation adjustments made to insure satisfactory service.

The ASTM Standard Method D 1037 (1975) for determining linear expansion requires equalizing a 3- by 12-inch specimen to

50 percent relative humidity, conditioning the specimen at 90 percent relative humidity, and determining the percent expansion of the specimen between the respective relative humidities. Many investigators have used 30 to 90 percent relative humidity increments and specimens not of the standard sizes. These adaptations of the standard method should not severely affect the final results provided the specimens have attained equilibrium at the relative humidity conditions used. Board density and particle configuration are discussed separately here regarding their effects on linear expansion.

Density.--Vital *et al.* (1974), in their study of particleboard pressed to two compaction ratios, found a slightly greater linear expansion with the higher compaction ratio--i.e., higher board density. They used both 30 to 90 and 50 to 90 percent relative humidity increments and, although the effect of compaction ratio on linear expansion was small and somewhat variable, a trend toward greater linear expansion with the higher compaction ratio was evident for both relative humidity exposures.

Stewart and Lehmann (1973), in their study of particleboard made with cross-grain, knife-planed flakes of four hardwood species, found an increase in linear expansion with increasing board density for a 30 to 90 percent relative humidity exposure with all species except the low-density basswood. This same effect was found for particleboard made with the two high-density species, red oak and hickory, after a 30-day water soak exposure. However, the linear expansion for the 30-day water soak test decreased with density for the boards made with yellow-poplar and basswood.

Stewart and Lehmann (1973) also reported swelling data for basswood particleboards which show the linear expansion from both 30 to 90 percent relative humidity exposure and the 30-day water soak test to be practically equal. Basswood particleboards of 40 and 45 lb/ft³ nominal density had 0.10 and 0.08 percent linear expansion, respectively, for the 30 to 90 percent relative humidity exposure. However, the same boards, subjected to a 30-day water soak test, had 0.12 and 0.09 percent linear expansion. All other particleboards made in this study had linear expansions in the 30-day water soak test twice those obtained from the 30 to 90 percent relative humidity exposures. This unique swelling behavior of the basswood particleboards was not discussed by the authors.

Suchsland (1972) found no clear relationship between board density and linear expansion for ten commercial particleboards exposed to a 40 to 93 percent relative humidity increment. However, the two boards with the highest density also had the highest linear expansion; the remaining eight boards had approximately the same density but the linear expansions were widely different. Gertjens *et al.* (1973) found no effect of board density on linear expansion with phenolic-bonded waferboard composed of tamarack, paper birch, and aspen. Lehmann (1974) also found no effect of board density on the linear expansion of phenol-formaldehyde-bonded particleboard made with Douglas-fir flakes of various lengths and thicknesses.

Hse (1975) determined the linear expansion of particleboards produced from nine southern hardwoods subjected to three different exposure tests. In all three tests (VPS, 50 to 90 percent relative humidity, and 5-hour boil), the linear expansion of sweetbay and red maple boards of 44.5 lb/ft³ was less than that of the boards of 39.5 lb/ft³ which was less than that of the boards of 49.5 lb/ft³. Particleboards from the other species did not consistently exhibit this behavior. The author did not comment upon this minimum linear expansion at the 44.5 lb/ft³ density for sweetbay and red maple, and no obvious explanation is evident from the data.

In general, there appears to be no consistent and reproducible relationship between particleboard density and linear expansion. There are indications that increasing density may tend to increase linear expansion but the evidence is not overwhelming. No investigators have found a statistically valid relationship between linear expansion and board density. Linear expansion is much more dependent upon particle geometry and alignment.

Particle configuration.--Gatchell *et al.* (1966) found increased linear expansion in Douglas-fir particleboard at all relative humidities when the flake thickness increased above 0.015 inch. Very little difference in linear stability was noted when the flake thickness was reduced to 0.007 inch. Linear expansion was also independent of flake length when the flake length was increased from 1 to 2 inches. However, with flakes 0.5 inch long, the resulting particleboard had significantly higher linear expansion. When the particle configuration was changed from flakes to slivers to hammermilled planer shavings, the linear stability also decreased. The authors attributed the linear expansion of the panels

with slivers to the cylindrical shape of the slivers in which the restraint of the longitudinal grain on the transverse grain was reduced from that of the flakes. The hammermilled planer shavings were somewhat cubical and did not felt with the longitudinal grain parallel to the panel surface as is typical with flakes. Consequently, the random orientation of the grain within the particleboard increased the linear expansion but at the same time reduced the thickness swell.

Turner (1954) also showed the tremendous improvement possible in linear stability by decreasing the flake thickness from 0.030 to 0.009 inch. Particleboard with flakes 1.5 inches long had slightly better linear stability than with flakes 3 inches long for flake thickness of 0.030 inch. However, when the thickness was reduced to 0.018 inch, the linear expansion of the particleboard with the 1.5-inch flake was reduced to much more than for the 3-inch flake, and was comparable to that of the 3-inch flake 0.009 inch thick. Heebink and Hann (1959) also found that red oak flakes 1 inch long produced more linearly stable particleboard than did 0.25-inch-long flakes, shavings, sawdust or slivers. Post (1961) also found that linear stability was not greatly affected by changes in flake length or thickness below a thickness of 0.012 inch; above this thickness, decreasing length reduced linear stability. Brumbaugh (1960) also found increased linear expansion in particleboard from Douglas-fir flakes as the flake length decreased and the flake thickness increased.

Lehmann (1974) subjected particleboards made with Douglas-fir flakes of three lengths (0.5, 1, and 2 inches) and two thicknesses (0.030 and 0.045 inch) to five exposure conditions. These exposure tests were 30 to 90 and 50 to 90 percent relative humidity steps, 1- and 30-day water soak, and oven-dry-vacuum pressure soak (OD-VPS). In all tests the panels with the 2-inch flakes had the best linear stability. Decreased flake thickness and increased flake length produced better linear stability in the water soak tests but flake thickness had no effect in the relative humidity tests. These results indicate that the exposure test used to study linear stability influences the results obtained.

Heebink (1974) found reduced linear stability with flakes 3 inches long by 0.030 inch thick as compared to flakes 2 inches long by 0.020 inch thick. This indicates flake thickness is a more important factor than either flake length or length/thickness ratio in controlling linear expansion. Heebink used the OD-VPS test.

Suchsland (1972) also concluded that particle size was the most important factor controlling linear expansion in his study of ten commercial particleboards. The exposure test he used was 40 to 93 percent relative humidity.

Gertjansen and Haygreen (1973) reported somewhat better dimensional stability with flakes (0.5 inch long by 0.015 inch thick) than with wafers (1.5 inches long by 0.025 inch thick). The resin content was 8 and 3 percent respectively (resin solids on OD wood) for the flakes and wafers, and, assuming equal particle widths, the flakeboard had somewhat higher resin content per unit of surface area. However, both board types had excellent linear stability and the absolute differences were small.

Howard (1974) found that linear expansion of particleboard made from slash pine rootwood was greater than that made from the stemwood when both were subjected to the VPS test. One possible explanation for this behavior was the higher grain deviation present in the flakes from the rootwood.

Stewart and Lehmann (1973) found particleboard produced with cross-grain planer flakes were exceptionally stable in both relative humidity exposure and 1- and 30-day water soak. This is attributed to small intraparticle separations between fibers produced by the cutting action of the planer, preventing swelling from accumulating over the entire flake.

The various researchers appear to agree that particleboards composed of flakes have the highest linear stability and that thin flakes (less than 0.012 to 0.015 inch) further improve the stability. The effect of flake length does not enjoy a consensus but it does appear that a flake length below 1.0 inch has a detrimental effect on linear expansion.

Resin and wax.--The linear expansion of particleboard subjected to various exposure conditions is only slightly reduced by increasing the resin content (Gatchell *et al.* 1966; Lehmann 1974). An exception to this appears to be that, at extremely low resin contents, linear expansion is substantially increased, but above a resin content high enough to adequately bond the particles, further resin addition is of little benefit.

Urea-formaldehyde resins usually result in less dimensional stability than the phenol-formaldehyde class because of resin hydrolysis when boards are exposed to moisture.

The effect of wax addition on linear expansion has not been widely studied because linear expansion is relatively low in most particleboards. However, wax addition would be expected to have a similar influence on linear expansion as has been reported for the thickness swelling--i.e., wax will reduce dimensional changes under cyclic relative humidity conditions and short-term liquid water exposure.

LITERATURE CITED

1. American Society for Testing and Materials
1975. Standard methods of evaluating the properties of woodbase fiber and panel materials. ASTM D 1037-72. Philadelphia, Pa.
2. Anderson, A. B., A. Wong, and K.-T. Wu.
1974a. Utilization of white fir bark in particleboard. *For. Prod. J.* 24(1):51-54.
3. Anderson, A. B., A. Wong, and K.-T. Wu.
1974b. Utilization of white fir bark and its extract in particleboard. *For. Prod. J.* 24(7):40-45.
4. Anderson, A. B., A. Wong, and K.-T. Wu.
1974c. Utilization of Ponderosa pine bark and its extract in particleboard. *For. Prod. J.* 24(8):48-53.
5. Anthony, C. P. and A. A. Moslemi
1969. Strength and dimensional properties of hickory flakeboards. *For. Prod. J.* 19(7):54-55.
6. Beech, J. C.
1975. The thickness swelling of wood particleboard. *Holzforschung* 29(1):11-18.
7. Bismarck, C.
1974. (Optimizing the pressing of particleboards. The manufacture of particleboards with urea-formaldehyde binders using special automated regulation systems for the pressing process.) *Holz-Zentralbl.* 100(80):1247-1249.
8. Browne, F. L., D. L. Kenaga, and R. M. Gooch
1966. Impregnation to control dimensional stability of particleboard and fiberboard. *For. Prod. J.* 16(11):45-53.
9. Brumbaugh, J. I.
1960. Effect of flake dimensions on properties of particleboard. *For. Prod. J.* 10(5): 243-246.

10. Bryan, E. L.
1960. Bending strength of particleboard under long-term load. *For. Prod. J.* 10(4): 200-204.
11. Bryan, E. L. and A. P. Schniewind
1965. Strength and rheological properties of particleboard as affected by moisture content and sorption. *For. Prod. J.* 15(4): 143-148.
12. Burmester, A.
1973. Effect of heat-pressure treatments of semi-dry wood on its dimensional stability. *Holz Roh- Werkst.* 31(6):237-243.
13. Burrows, C. H.
1961. Some factors affecting resin efficiency in flakeboard. *For. Prod. J.* 11(1): 27-33.
14. Carroll, M. N.
1963. Efficiency of urea- and phenol-formaldehyde in particleboard. *For. Prod. J.* 13(3):113-120.
15. Carroll, M. N.
1970. Relationship between driving torque and screw-holding strength in particleboard and plywood. *For. Prod. J.* 20(3): 24-29.
16. Carroll, M. N. and D. McVey
1962. An analysis of resin efficiency in particleboard. *For. Prod. J.* 12(7):305-310.
17. Chen, T. Y., M. Paulitsch, and G. Soto
1972. On the suitability of the biological surface mass from spruce thinnings as raw material for particleboard. *Holz Roh-Werkst.* 30(1):15-18.
18. Childs, M. R.
1956. The effect of density, resin content, and chip width on springback and certain other properties of dry formed flat pressed particleboard. M.S. Thesis, Dept. of Wood and Pap. Sci., North Carolina State Univ., Raleigh.
19. Christensen, R. L.
1972. Test for measuring formaldehyde emission from formaldehyde bonded particleboards and plywood. *For. Prod. J.* 22(4):17-20.
20. Christensen, R. L. and P. Robitschek
1974. Efficiency of resin-wood particle bonding. *For. Prod. J.* 24(7):22-25.
21. Clad, W.
1967. Phenolic-formaldehyde condensates as adhesives for particleboard manufacture. *Holz Roh- Werkst.* 25(4): 137-147.
22. Deppe, H. J. and K. Ernst
1965. Problems of pressing-time reduction in particleboard manufacture. *Holz Roh- Werkst.* 23(11):441-445.
23. Deppe, H. J. and K. Ernst
1971. Isocyanates as adhesives for particleboard. *Holz Roh- Werkst.* 29(2):45-50.
24. Didriksson, E. I. E., J. O. Nyren, and E. L. Back
1974. The splitting of wood-base building boards due to edge screwing. *For. Prod. J.* 24(7):35-39.
25. Dost, W. A.
1971. Redwood bark fiber in particleboard. *For. Prod. J.* 21(10):38-43.
26. Duncan, T. F.
1974. Normal resin distribution in particleboard manufacture. *For. Prod. J.* 24(6): 36-44.
27. Fahrni, F.
1956. (The pressing of particleboards with particles of high moisture content in the surface layers.) *Holz Roh- Werkst.* 14(1): 8-10.
28. Gatchell, C. J., B. G. Heebink, and F. V. Hefty
1966. Influence of component variables on properties of particleboard for exterior use. *For. Prod. J.* 16(4):46-59.
29. Geimer, R. L., H. M. Montrey, and W. F. Lehmann
1975. Effects of layer characteristics on the properties of three-layer particleboards. *For. Prod. J.* 25(3):19-29.
30. Gertjeansen, R. and J. G. Haygreen
1973. Effect of aspen bark from butt and upper logs on the physical properties of wafer-type and flake-type particleboards. *For. Prod. J.* 23(9):66-71.
31. Gertjeansen, R., M. Hyvarinen, J. Haygreen, and D. French
1973. Physical properties of phenolic bonded wafer-type particleboard from mixtures of aspen, paper birch, and tamarack. *For. Prod. J.* 23(6):24-28.
32. Ginzel, W.
1973. Contribution to the hydrolysis in urea-resin-bonded particleboard. *Holz Roh- Werkst.* 31(1):18-24.
33. Halligan, A. F.
1970. A review of thickness swelling in particleboard. *Wood Sci. Technol.* 4(4): 301-312.

34. Halligan, A. F. and A. P. Schniewind
1972. Effect of moisture on physical and creep properties of particleboard. *For. Prod. J.* 22(4):41-48.
35. Halligan, A. F. and A. P. Schniewind
1974. Prediction of particleboard mechanical properties at various moisture contents. *Wood Sci. Technol.* 8(1):68-78.
36. Hann, R. A., J. M. Black, and R. F. Blomquist
1962. How durable is particleboard? *For. Prod. J.* 12(12):577-584.
37. Hann, R. A., J. M. Black, and R. F. Blomquist
1963. How durable is particleboard? II. The effect of temperature and humidity. *For. Prod. J.* 13(5):169-174.
38. Hart, C. A. and J. T. Rice
1963. Some observations on the development of a laboratory flakeboard process. *For. Prod. J.* 13(11):483-488.
39. Haygreen, J. G. and R. O. Gertjejansen
1971. Improving the properties of particleboard by treating the particles with phenolic impregnating resin. *Wood & Fiber* 3(2):95-105.
40. Haygreen, J. G. and R. O. Gertjejansen
1972. Influence of the amount and type of phenolic resin on the properties of a wafer-type particleboard. *For. Prod. J.* 22(12):30-34.
41. Heebink, B. G.
1967. A procedure for quickly evaluating dimensional stability of particleboard. *For. Prod. J.* 17(9):77-80.
42. Heebink, B. G.
1972. Irreversible dimensional changes in panel materials. *For. Prod. J.* 22(5):44-48.
43. Heebink, B. G.
1974. Particleboards from lodgepole pine forest residue. USDA For. Serv. Res. Pap. FPL 221. For. Prod. Lab., Madison, Wis.
44. Heebink, B. G. and R. A. Hann
1959. How wax and particle shape affect stability and strength of oak particleboards. *For. Prod. J.* 9(7):197-203.
45. Heebink, B. G., R. A. Hann, and H. H. Haskell
1964. Particleboard quality as affected by planer shaving geometry. *For. Prod. J.* 14(10):486-494.
46. Heebink, B. G. and F. V. Hefty
1969. Treatments to reduce thickness swelling of phenolic-bonded particleboard. *For. Prod. J.* 19(11):17-26.
47. Heebink, B. G., W. F. Lehmann, and F. V. Hefty
1972. Reducing particleboard pressing time: Exploratory study. USDA For. Serv. Res. Pap. FPL 180. For. Prod. Lab., Madison, Wis.
48. Henkel, M.
1969. Measurement of density profiles in particleboards and fibreboards by X-rays. *Holztechnologie* 10(2):93-96.
49. Howards, E. T.
1974. Slash pine rootwood in flakeboard. *For. Prod. J.* 24(6):29-35.
50. Hse, C.-Y.
1974a. Characteristics of urea-formaldehyde resins as related to glue bond quality of southern pine particleboard. *J. Jap. Wood Res. Soc.* 20(10):483-490.
51. Hse, C.-Y.
1974b. Reaction pH of urea-formaldehyde resins as related to strength properties of southern pine particleboard. *J. Jap. Wood Res. Soc.* 20(10):491-493.
52. Hse, C.-Y.
1974c. Reaction catalysts of urea-formaldehyde resins as related to strength properties of southern pine particleboard. *J. Jap. Wood Res. Soc.* 20(11):538-540.
53. Hse, C.-Y.
1975. Properties of flakeboards from hardwoods growing on southern pine sites. *For. Prod. J.* 25(3):48-53.
54. Hse, C.-Y., P. Koch, C. W. McMillin and E. W. Price
1975. Laboratory scale development of a structural exterior flakeboard from hardwoods growing on southern pine sites. *For. Prod. J.* 25(4):42-50.
55. Hujanen, D. R.
1973. Comparison of three methods for dimensionally stabilizing wafer-type particleboard. *For. Prod. J.* 23(6):29-30.
56. Hunt, D. G.
1965. The show-through of veneered particleboard. *J. Inst. Wood Sci.* 8(14):47-72.

57. Istrate, V., G. Filipescu, and C. Stefu
1964. (The influence of chip dimension on the consumption of glue and on the quality of particleboard.) *Industr. Lemn.* 17(4):133-137.
58. Johnson, J. W.
1964. Effect of exposure cycles on stability of commercial particleboard. *For. Prod. J.* 14(7):277-282.
59. Johnson, A. and J. G. Haygreen
1974. Impact behavior of particleboard as related to some other physical properties. *For. Prod. J.* 24(11):22-27.
60. Jorgensen, R. M. and R. L. Odell
1961. Dimensional stability of oak flakeboard as affected by particle geometry and resin spread. *For. Prod. J.* 11(10):463-466.
61. Kehr, E.
1966. On the improvements of particleboard surfaces. *Holz Roh- Werkst.* 24(7):295-305.
62. Kehr, E. and U. Jensen
1969. On thickness variations of calibrated particleboards. *Holztechnologie* 10(2):97-104.
63. Kehr, E. and U. Jensen
1970. Manufacture and properties of particleboard with fine particle surface layers. *Holz Roh- Werkst.* 28(10):385-391.
64. Kehr, E., K. H. Macht, and G. Riehl
1964. Contributions to the gluing and bonding process with chips in particleboard manufacture. I. About the influence of the throughput of binders when whirling nozzles are used. *Holztechnologie* 5(1):17-26.
65. Kehr, E., K. H. Macht, and G. Riehl
1968. Contributions on glue-spreading and gluing of chips in manufacturing particleboards. V. Investigations on the circulating of chips in the mixer, arrangement of nozzles, and the stripping effect with the spray and circulating glue spreading methods. *Holztechnologie* 9(3):169-175.
66. Kehr, E. and S. Schoelzel
1965. The investigation on pressing conditions in the manufacture of particleboards. *Drev. Vysk.* 1965(3):133-147.
67. Kehr, E. and S. Schoelzel
1967. Investigations of the pressing diagram. II. Influence of chip moisture, mould closing time, and moulding pressure on the compression characteristics during hot-pressing particleboards. *Holztechnologie* 8(3):177-181.
68. Keylwerth, R.
1958. On the mechanics of the multi-layer particleboard. *Holz Roh- Werkst.* 16(11):419-430.
69. Kimoto, R., E. Ishimoir, H. Sasaki, and T. Maku
1964. Studies on particleboards. VI. Effects of resin content and particle dimension on the physical and mechanical properties of low-density particleboards. *Wood Res. Kyoto U.* 32:1-14
70. Klar, G. V. and J. Stofko
1965. ("Combined" wood particleboards with higher strength.) *Dievo* 20(1):5-7.
71. Klauditz, W., H. J. Ulbricht, W. Kratz, and A. Buro
1960. The production and properties of woodchip material with oriented strength. *Holz Roh- Werkst.* 18(10):377-385.
72. Kollmann, F. P., E. W. Kuenzi, and A. J. Stamm
1975. Principles of wood science and technology. Vol. II. Wood-based materials. Chap. 5. Springer-Verlag, New York, 703 p.
73. Kusian, R.
1968. Model-investigations about the influence of particle size on structural and strength properties of particle materials. II. Experimental investigations. *Holztechnologie* 9(4):241-248.
74. Larmore, F. D.
1959. Influence of specific gravity and resin content on properties of particleboard. *For. Prod. J.* 9(4):131-134.
75. Lehmann, W. F.
1960. The effects of moisture content, board density, and press temperature on the dimensional and strength properties of flat-pressed particleboard. M.S. Thesis, Dep. of Wood and Pap. Sci., North Carolina State Univ., Raleigh.

76. Lehmann, W. F.
1965. Improved particleboard through better resin efficiency. *For. Prod. J.* 15(4): 155-161.
77. Lehmann, W. F.
1968. Resin distribution in flakeboard shown by ultralight photography. *For. Prod. J.* 18(10):32-34.
78. Lehmann, W. F.
1970. Resin efficiency in particleboard as influenced by density, atomization, and resin content. *For. Prod. J.* 20(11):48-54.
79. Lehmann, W. F.
1974. Properties of structural particleboard. *For. Prod. J.* 24(1):19-26.
80. Lehmann, W. F. and R. L. Geimer
1974. Properties of structural particleboards from Douglas-fir forest residues. *For. Prod. J.* 24(10):17-25.
81. Lehmann, W. F., R. L. Geimer, and F. V. Hefty
1973. Factors affecting particleboard pressing time: Interaction with catalyst systems. USDA For. Serv. Res. Pap. FPL 208. For. Prod. Lab., Madison, Wis.
82. Lehmann, W. F. and F. V. Hefty
1973. Resin efficiency and dimensional stability of flakeboards. USDA For. Serv. Res. Pap. FPL 207. For. Prod. Lab., Madison, Wis.
83. Liiri, O.
1961. Investigations into long-term moistening of wood particle board and the effect of changes in moisture on its qualities. *Pap. Puu* 43(12):737-748.
84. Liiri, O.
1969. The pressure in the particleboard production. *Holz Roh- Werkst.* 27(10): 371-378.
85. Lutz, J. F., B. G. Heebink, H. R. Panzer, F. V. Hefty, and A. F. Mergen
1969. Surfacing softwood dimension lumber to produce good surfaces and high value flakes. *For. Prod. J.* 19(2):45-50.
86. Lynam, F. C.
1959. Factors influencing the properties of chipboard. *J. Inst. Wood Sci.* 2(4):14-27.
87. Maku, T. and R. Hamada
1955. Studies on chipboard. II. Swelling properties of chipboard. *Wood Res. Kyoto U.* 15:53-59.
88. Maku, T., R. Hamada, and H. Sasaki
1957. Studies on the chipboard. III. Some experiments on the improvements of dimensional stabilities of chipboard. *Wood Res. Kyoto U.* 17:16-24.
89. Maku, T., R. Hamada, and H. Sasaki
1959. Studies on the particleboard (chipboard). IV. Temperature and moisture distribution in particleboard during hot-pressing. *Wood Res. Kyoto U.* 21:34-46.
90. Maku, T., H. Sasaki, and R. Hamada
1956. The effect of paraffin emulsion on the hygroscopic, swelling, and mechanical properties of chipboard. *J. Jap. Wood Res.* 2(3):130-132.
91. Maloney, T. M.
1970. Resin distribution in layered particleboard. *For. Prod. J.* 20(1):43-52.
92. Maloney, T. M.
1975. Use of short-retention-time blenders with large-flake furnishes. *For. Prod. J.* 25(5):21-29.
93. Marian, J. E.
1958. Adhesive and adhesion problems in particleboard production. *For. Prod. J.* 8(6):172-176.
94. McNatt, J. D.
1973. Basic engineering properties of particleboard. USDA For. Serv. Res. Pap. FPL 206. For. Prod. Lab., Madison, Wis.
95. McNatt, J. D.
1974. Properties of particleboards at various humidity conditions. USDA For. Serv. Res. Pap. FPL 225. For. Prod. Lab., Madison, Wis.
96. Meinecke, E. and W. Klauditz
1962. (Physics and technology of glue application and mutual bonding of wood particles in the manufacture of particleboards.) *Inst. Wood Res., Forschungsber. Landes Nordrhein-Westfalen Rept. 1053, Köln and Opladen, W. German.* Transl. available from U.S. Dept. of Commerce.
97. Mikhailov, N. A. and N. I. Ostapenko
1972. (Internal stresses in particleboard.) *Derevoobrab. Prom.* 21(10):9-10.
98. Neusser, H.
1967. Practical testing of urea resin glues for particleboard, with regard to shortening of pressing time. *Holzforsch. Holzverwert.* 19(3):37-40.
99. Neusser, H. and V. Krames
1971. Surface texture of particleboard, its assessment and aesthetic effect. *Holz Roh- Werkst.* 29(3):103-118.

100. Neusser, H., V. Krames, and K. Haidinger
1965. The effect of moisture on particleboards with special consideration of swelling. *Holzforsch. Holzverwert.* Pt. I. 17(3):43-53; Pt. II. 17(4):57-69.
101. Neusser, H., V. Krames, K. Haidinger, and W. Serentschy
1969. The character of particles and his influence on quality of surface layers of particleboards. *Holzforsch. Holzverwert.* 21(4):81-94.
102. Neusser, H., V. Krames, and M. Zentner
1969. Particleboards with different surface layers as basic material for overlays. *Holzforsch. Holzverwert.* 21(3):56-61.
103. Neusser, H. and M. Zentner
1968. On the causes and control of formaldehyde odour with wood-based material, especially particleboards. *Holzforsch. Holzverwert.* 20(5):101-112.
104. Norimoto, M. and T. Yamada
1966. On the creep of particle boards. *Wood Res. Kyoto U.* 39:22-28.
105. Otle, I. A.
1971. (Change in the moisture content of the chip mat during hot pressing.) *Derevoobrab. Prom.* 20(10):3-4.
106. Pecina, H.
1963. Determination of the dimensions of particle surface wetted by the adhesive. *Holztechnologie* 4(1):68-70.
107. Petersen, H., W. Reuther, W. Eisele, and O. Wittmann
1972. Investigations on the formaldehyde liberation during the manufacture of particleboard with urea-formaldehyde adhesives. *Holz Roh- Werkst.* 30(11):429-436.
108. Petersen, H., W. Reuther, W. Eisele, and O. Wittmann
1973. Further investigations on the formaldehyde liberation during particleboard production with urea-formaldehyde adhesives. II. Effect of resin quantity, pressing time, and temperature. *Holz Roh- Werkst.* 31(12) :463-469.
109. Petersen, H., W. Reuther, W. Eisele, and O. Wittmann
1974. Further investigations on the formaldehyde liberation during particleboard production with urea-formaldehyde adhesives. III. Influence of hardener type and amount of formaldehyde-binding agents. *Holz Roh- Werkst.* 32(10):402-410.
110. Plath, L.
1966. The determination of formaldehyde liberation from particleboards by the microdiffusion method. *Holz Roh- Werkst.* 24(7) :312-318.
111. Plath, L.
1967a. Tests on formaldehyde liberation from particleboard. II. The influence of pressing time and temperature on formaldehyde liberation. *Holz Roh- Werkst.* 25(2) :63-68.
112. Plath, L.
1967b. Tests on formaldehyde liberation from particleboard. III. Influence of hardener compounds on formaldehyde liberation. *Holz Roh- Werkst.* 25(5):169-173.
113. Plath, L.
1967c. Tests on formaldehyde liberation from particleboard. IV. Effect of moisture content in chip mat on formaldehyde liberation. *Holz Roh- Werkst.* 25(6):231-238.
114. Plath, L.
1968. Tests on formaldehyde liberation from particleboard. V. The influence of curing acceleration and aging period on formaldehyde liberation. *Holz Roh- Werkst.* 26(4):125-128.
115. Plath, L.
1971a. Requirements for particleboards with plastic layers. *Holz Roh- Werkst.* 29(10) :369-376.
116. Plath, L.
1971b. A contribution on particleboard mechanics. *Holz Roh- Werkst.* 29(10):377-382.
117. Plath, L. and E. Schnitzler
1974. The density profile, a criterion for evaluating particleboard. *Holz Roh- Werkst.* 32(11):443-449.
118. Polge, H. and P. Lutz
1969. Possibilities of the density measurement of particleboards perpendicular to the plane by X-rays. *Holztechnologie* 10(2):75-79.
119. Post, P. W.
1958. The effect of particle geometry and resin content on bending strength of oak particleboard. *For. Prod. J.* 8(10):317-322.

20. Post, P. W.
1961. Relationship of flake size and resin content to mechanical and dimensional properties of flakeboard. *For. Prod. J.* 11 (1) :34-37.
121. Rackwitz, G.
1963. Influence of chip dimensions on some properties of wood particleboard. *Holz Roh- Werkst.* 21(6):200-209.
122. Rice, J. T.
1960. The effects of selected variables on the properties of flatpressed flakeboards. M.S.Thesis, Dep. of Wood and Pap. Sci., North Carolina State Univ., Raleigh.
123. Rice, J. T.
1973. Particleboard from "silage" sycamore--laboratory production and testing. *For. Prod. J.* 23(2):28-34.
124. Rice, J. T., J. L. Snyder, and C. A. Hart
1967. Influence of selected resin and bonding factors on flakeboard properties. *For. Prod. J.* 17(8):49-57.
125. Roffael, E. and W. Rauch
1971a. Production of particleboards using sulfite black liquor as binder. I. Literature review and own investigations. *Holzforschung* 25(4):112-116.
126. Roffael, E. and W. Rauch
1971b. Production of particleboards using sulfite black liquor as binder. II. A new and fast method for the production of particleboards. *Holzforschung* 25(5):149-155.
127. Roffael, E. and W. Rauch
1972a. Influence of density on the swelling behavior of phenolic-resin-bonded particleboards. *Holz Roh- Werkst.* 30(5):178-181.
128. Roffael, E. and W. Rauch
1972b. Production of particleboards using sulfite black liquor as binder. III. Possibilities of shortening the post-thermal treatment for sulfite liquor bonded particleboards of 9 mm thickness. *Holzforschung* 26(6): 197-202.
129. Roffael, E. and W. Rauch
1973a. (Use of sulfite black liquors in combination with alkaline phenolic resins as adhesives in particleboard gluing.) *Holzforschung* 27(5):178-179.
130. Roffael, E. and W. Rauch
1973b. Production of particleboard using black liquor as binder. IV. Use of sulfite liquor in combination with alkaline phenolic resins. *Holzforschung* 27(6): 214-217.
131. Roffael, E. and W. Rauch
1973c. Influence of temperature and thermal post-treatment on some physical properties of diisocyanate bonded particleboard. *Holz Roh- Werkst.* 31(10):402-405.
132. Roffael, E. and W. Rauch
1974. (Comparing certain properties of chipboards made with phenolic resins and sulfite liquor.) *Holz-Zentralbl.* 100 (43/44):702-704.
133. Roffael, E., K. Schaller and W. Rauch
1972. (Manufacture of phenol-resin-bonded particleboards. I. The effect of pressing temperature on some physical and technological properties.) *Holz-Zentralbl.* 98(136):2003-2004.
134. Saito, F.
1972. Spring back of particle boards. *Wood Ind. (Jap)* 27(1):14-18.
135. Schneider, A.
1973. The sorption-behavior of phenolic-bonded and urea-bonded particleboards. *Holz Roh- Werkst.* 31(11):425-429.
136. Schorning, P., E. Roffael, and G. Stegmann
1972. New wood-to-wood bonds in chip materials by chemical polyfunctional systems. I. Hot pressing with amine-alkaline bond systems. *Holz Roh- Werkst.* 30(7):253-258.
137. Schorning, P. and G. Stegmann
1972. New wood-to-wood bonds in chip materials by chemical polyfunctional systems. II. Hot pressing with wooden boards and particles in a weak acid bond system. *Holz Roh- Werkst.* 30(9):329-332.
138. Seifert, J.
1972. On the sorption and swelling of wood and wood base materials. I. Influences on the sorption of wood-base materials. *Holz Roh- Werkst.* 30(3):99-111.

139. Shen, K. C.
1973. Steam-press process for curing phenolic-bonded particleboard. *For. Prod. J.* 23(3):21-29.
140. Shen, K. C.
1974. Improving the surface quality of particleboard by high-temperature pressing. *For. Prod. J.* 24(10):36-39.
141. Shen, K. C. and M. N. Carroll
1969. A new method for evaluation of internal strength of particleboard. *For. Prod. J.* 19(8):17-22.
142. Shen, K. C. and M. N. Carroll
1970. Measurement of layer strength distribution in particleboard. *For. Prod. J.* 20(6):53-55.
143. Shuler, C. E.
1974. Pilot study of the use of pulpwood chipping residue for producing particleboard in Maine. *Tech. Bull. No. 67, Life Sci. and Agr. Exp. Sta., Univ. of Maine, Orono.*
144. Stayton, C. L. and M. J. Hyvarinen, R. O. Gertjeansen, and J. G. Haygreen
1971. Aspen and paper birch mixtures as raw material for particleboard. *For. Prod. J.* 21(12):29-30.
145. Stegmann, G. and J. Durst
1964. Particleboard from beech wood. *Holz-Zentralbl.* 90(153):313-318.
146. Stewart, H. A.
1970. Cross-grain knife planing hard maple produces high-quality surfaces and flakes. *For. Prod. J.* 20(10):39-42.
147. Stewart, H. A. and W. F. Lehmann
1973. High-quality particleboard from cross-grain, knife-planed hardwood flakes. *For. Prod. J.* 23(8):52-60.
148. Stewart, H. A. and W. F. Lehmann
1974. Cross-grain cutting with segmented helical cutters produces good surfaces and flakes. *For. Prod. J.* 24(9):104-106.
149. Strickler, M. D.
1959. Effect of press cycle and moisture content on properties of Douglas-fir flakeboard. *For. Prod. J.* 9(7):203-205.
150. Suchsland, O.
1959. An analysis of the particleboard process. *Q. Bull., Mich. Agr. Exp. Sta., Mich. State Univ.* 42(2):350-372.
151. Suchsland, O.
1960. An analysis of a two-species three-layer wood flakeboard. *Q. Bull., Mich. Agr. Exp. Sta., Mich. State Univ.* 43(2):375-393.
152. Suchsland, O.
1962. The density distribution in flakeboard. *Q. Bull., Mich. Agr. Exp. Sta., Mich. State Univ.* 45(1):104-121.
153. Suchsland, O.
1967. Behavior of a particleboard mat during the pressing cycle. *For. Prod. J.* 17(2):51-57.
154. Suchsland, O.
1972. Linear hygroscopic expansion of selected commercial particleboards. *For. Prod. J.* 22(11):28-32.
155. Suchsland, O.
1973. Hygroscopic thickness swelling and related properties of selected commercial particleboards. *For. Prod. J.* 23(7):26-30.
156. Suchsland, O. and R. C. Enlow
1968. Heat treatment of exterior particleboard. *For. Prod. J.* 18(8):24-28.
157. Superfesky, M. J.
1974. Screw withdrawal resistance of type A and AB sheet metal screws in particleboard and medium density hard board. *USDA For. Serv. Res. Pap. FPL 239. For. Prod. Lab., Madison, Wis.*
158. Talbott, J. W. and T. M. Maloney
1957. Effect of several production variables on the modulus of rupture and internal bond strength of boards made of green Douglas-fir planer shavings. *For. Prod. J.* 7(10):395-398.
159. Turner, H. D.
1954. Effect of particle size and shape on strength and dimensional stability of resin bonded wood-particle panels. *For. Prod. J.* 4(5):210-222.
160. Vital, B. R., W. F. Lehmann, and R. S. Boone
1974. How species and board densities affect properties of exotic hardwood particleboards. *For. Prod. J.* 24(12):37-45.

161. Walker, J. F.
1964. Formaldehyde. 3rd ed. Reinhold Publ. Corp., New York. 701 p.
162. Wittmann, O.
1962. The subsequent dissociation of formaldehyde from particleboard. Holz Roh- Werkst. 20(6):221-224.
163. Wittmann, O.
1973. Alkali in phenolic resin bonded particleboard. Holz Roh- Werkst. 31(11): 419-425.