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THE GLUING OF WOOD

By

T. R. TRUAX, Senior Wood Technologist
Forest Products Laboratory
Branch of Research, Forest Service

CONTENTS

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THE GLUING OF WOOD

By T. R. Truax, *Senior Wood Technologist, Forest Products Laboratory, Branch of Research, Forest Service*[1]

CONTENTS

INTRODUCTION

The use of glue in the fabrication of wood products brings about more complete utilization of timber through the use of lower grades, inferior species, and small sizes of material; it conserves supplies of clear material and of the scarcer and more valuable woods; and it makes possible a saving of material in the production of articles of unusual form, dimensions, and properties. Nearly every article of glued-wood construction represents an economy in the use of timber resources.

The purpose of this publication is to bring together essential information about glues and gluing, to set forth important principles of

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[1] Acknowledgment is made to George M. Hunt, in charge of section of wood preservation, and to various other members of the Forest Products Laboratory, for assistance in the preparation of this bulletin. Further acknowledgment is made to the University of Wisconsin.

control in the gluing operation, and to outline methods that have been found to give satisfactory results. The chief aim is to deal with the technic of gluing, rather than to present a technical discussion of glues. The publication has as a background a large amount of experimental work, from which far-reaching conclusions of practical importance have been deduced. Furthermore, these principles have been verified in large part in commercial operations. They are presented here as an aid in the improvement of gluing practice in the many plants which glue wood.

GLUES USED IN WOODWORKING

The adhesives most used in woodworking may be divided into five classes, as follows: Animal glues, liquid glues, vegetable (starch) glues, casein and vegetable-protein glues, and blood-albumin glues. There are various other adhesive substances[2] including silicate of soda, mucilages, pastes, rubber cements, cellulose cements, phenol-aldehyde compounds, asphalts, gums, and shellac, some of which are used to a limited extent for gluing wood; but this bulletin deals only with the five main classes listed above.

The properties and characteristics of the five principal classes of glue are given in Table 1. There is no one glue or class of glues that is superior in all respects to all the others. Each class, because of its superiority in one or more particulars, may be expected to find preference for certain purposes. In some cases two or more glues may be found to meet requirements equally well.

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[2] Marine glues are sometimes mistakenly thought to be wood-gluing adhesives. As a matter of fact they are used as water-excluding fillers between layers of wood and do not have the property of setting, which is required to produce a strong joint.

TABLE 1.—*Properties and characteristics of different classes of woodworking glues*

Property or characteristic	Animal glues	Liquid glues	Vegetable (starch) glues	Casein glues[1]	Blood-albumin glues
Mixing and application	Soaked in water and melted; applied warm by hand or mechanical spreaders.	Require no mixing; applied warm or cold, usually by hand.	Mix with water and alkali with or without heat; applied cold by mechanical spreaders.	Mixed cold with water; applied cold by hand or mechanical spreaders.	Mixed cold with water; applied cold by hand or mechanical spreaders.
Tendency to foam	Usually slight; sometimes pronounced.	Of little practical importance.	Very slight; some air usually embodied in mixing.	Very slight to medium	Slight to pronounced
Temperature requirements	Control important for glue, wood, and room.	Sometimes necessary to warm glue.	Used at ordinary room temperatures.	Used at ordinary room temperatures.	Heat usually required to set glues; cold-press formula an exception.
Spreading capacity:[2]					
Extremes reported[3]	20 to 55	No data	35 to 120	30 to 80	30 to 100.
Common range[3]	25 to 35		42 to 60	35 to 55	
Working life	A day or less[4]	Several hours to many days	Many days	Few hours to several days[4]	Several hours to a few days.
Consistency	Variable from thin to very thick with temperature changes.	Variable from thin to medium.	Normally thick	Thick to medium	Variable, thin to thick depending on formula.
Rate of setting	Rapid	Rapid to medium	Slow to rapid	Rapid	Very rapid with heat; otherwise slower.
Strength[5]	Very high to low	High to very low	Very high to medium	Very high to medium	Medium to low.
Water resistance	Low[6]	Low	Low	Low to high	Very high.
Tendency to stain wood	None to very slight	None to very slight	Slight to marked with some woods.	Marked with some woods	None, except that the dark glue may show through thin veneer.
Dulling effect on tools[3]	Moderate	Moderate	Moderate	Moderate to pronounced	Slight.

[1] Glues made from vegetable proteins, such as soy-bean and peanut meal, resemble casein glues in general properties and characteristics.
[2] Expressed in square feet of single glue line per pound of dry glue for veneer work.
[3] Based on reports from commercial operators.
[4] Animal and casein glues are likely to deteriorate seriously if kept liquid more than one day.
[5] Based chiefly on joint strength tests.
[6] The water resistance of animal glues may be increased by chemical treatment (see Appendix, p. 64).

The purposes for which glues are used in woodworking may be grouped broadly as the gluing of veneer and the gluing of joints in thick stock. Blood-albumin glues are used chiefly on veneer, whereas animal, vegetable, and casein glues are used both on veneer and on thick stock. Liquid glues are used mainly for joints of small area which are subjected to low stress, such as those in repair work and in small jobs of hand gluing. The other glues are used mainly in larger-scale production.

CONSIDERATIONS APPLICABLE TO ALL USES

It is necessary in all cases that the glue be capable of producing joints strong enough and durable enough for the use to which the wood is to be put. Glues should remain in usable condition long enough (working life) for use by ordinary gluing methods without undue waste or inconvenience. A glue which requires little attention to temperature in mixing and application is more convenient to use than one requiring careful temperature control. Cost, spreading capacity, ease of mixing and applying, and tendency to foam are other points that should be considered in selecting a glue for quantity production of practically any type of wood joint.

Both the original cost and the spreading capacity of the glue affect the final cost of the joint. Spreading capacity is chiefly dependent (except in liquid glue) upon the proportion of water that can be added without reducing the strength of the joint. Cost is of greatest importance in the manufacture of cheap products and in veneer gluing and other large-scale operations.

Ease of application, by which is meant the simplicity and ease with which a satisfactory coating of the glue may be spread upon the wood is always important, but less so on flat surfaces, where standard mechanical spreaders are the rule, than on irregular joints, where special spreaders are used or where spreading is done by hand.

The degree to which glue tends to foam on account of the air whipped into it in mixing and on mechanical spreaders is also important. Foamy glue may contain air bubbles or may have a froth or lather on its surface. It produces inferior joints in all classes of work because the air bubbles prevent complete contact of glue and wood.

PROPERTIES IMPORTANT IN SPECIAL CASES

Considerations that may affect the suitability of a glue for particular uses are the rate of setting in the joint, the water resistance of the set glue, the tendency to stain wood, and the dulling effect on tools. Each may become the deciding factor in the selection of a glue for a particular use. For example, in edge-gluing lumber the desired speed of production usually requires a quick-setting glue. Water resistance of the joint is a first consideration in exterior doors, aircraft, and many other constructions. Thin face veneers require a glue that does not stain. Glues which have a marked dulling effect on tools are undesirable for certain products. The dulling effect causes frequent changing of planer or shaper knives, with consequent increase in expense and decrease in production speed.

ANIMAL GLUES

The desirable properties of animal glue for woodworking are high strength in joints, free-flowing consistency, quick setting, stainlessness, and adaptability to different use conditions. In practice no other glue has been found to be as satisfactory as animal glue for hand spreading on irregularly shaped joints, although a cheaper glue would be very desirable. The cost of animal glue and the precautions necessary in applying it are the chief factors which limit its use. For some purposes the fact that it is not naturally highly water resistant is also a drawback. A formula for increasing the water resistance of animal glue is given in the Appendix.

Animal glue may be sold in different forms, of which the cake, flake, and ground forms are the most common. Shredded and pearl (*47*)[3] glues are two forms recently developed. There is no distinguishable difference in strength or other property between these forms. Ground, pearl, and shredded glue can be mixed and melted more quickly and conveniently than the others, but some consumers avoid the ground glue because they consider it easier to adulterate. While adulteration is possible, ground glue which conforms to acceptable specifications or standards may be used with confidence. Ground glue was used by the Government during the World War for gluing airplane propellers because it was easier to sample and test and more convenient to mix than the other forms then available. Most of the animal glue used in woodworking is made by cooking in water the hides or bones of cattle, but some is made from fleshings, sinews, cartilage, horn piths, and other animal parts, and the liquor thus obtained is drawn off, concentrated by evaporation, jellied, and further dried (*1*, *6*, *41*). The same raw material with fresh water added is reheated to yield liquors for other batches of glue. The first batch of glue gives the highest grade. There is also a wide range in the grade of glue obtained from each class of raw material.

All manufacturers of animal glue grade their product on account of variations in quality. The tests upon which grades are based are discussed in the Appendix.

The oldest system of grades in America, and one of the best known, is that established about 1844 by Peter Cooper (*1*), in which glues were classified in order from the highest to the lowest grades as AA extra, A extra, I extra, No. I, IX moulding, IX, 1¼, 1⅜, 1½, 1⅝, 1¾, 1⅞ and 2. The Peter Cooper system was not generally accepted as a standard. A major objection was that it depended upon a set of samples the measurable physical properties of which were not clearly defined. Recently the National Association of Glue Manufacturers, comprising a considerable number of the animal-glue makers of the United States, worked out and adopted uniform, clearly defined, and accurate testing methods by means of which test results (*17*) can be duplicated in any suitably equipped laboratory. On the basis of tests of the jelly strength and viscosity of glues the association has established a system of grades. The new grades are numbered 1 to 21 in ascending order of quality. Most of the glues used in gluing wood are included in the middle third of this range (*30*). The new grading system promises to bring about a very desirable

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[3] Reference is made by italic number in parentheses to "Literature cited," p. 75.

simplification, with substantial benefits to both the producer and the user of animal glues. The specification for glues for Government use are now based upon these new methods of test.

LIQUID GLUES

Of the large class of glues sold in liquid form a high percentage are made from the heads, bones, skins, trimmings, and swimming bladders of fish, and the whole class is often referred to as fish glues. Some liquid glues, however, are made by treating animal glue with a chemical agent, usually an acid, and some are made from other raw materials. The relative merits of the glues made from these different materials have not been thoroughly studied.

Most liquid glues are similar in properties to animal glues. Only the best liquid glues, however, are reliable enough and make strong enough joints for use in wood products. The ability to make strong joints is generally indicated by the viscosity or "body" of the glue, thick glues giving high strength and thin glues low strength. A desirable property in a liquid glue is that of remaining in workable condition as long at it is in the container, but drying and setting quickly on wood surfaces. Other desirable properties of liquid glues and the ways in which they are determined are discussed in the Appendix.

Liquid glues are commonly sold in small containers under various trade names, without other indication of grade or quality. Their chief advantage is that they come in prepared form, ready for immediate use, which makes them particularly suitable for patchwork and small gluing jobs.

CASEIN AND VEGETABLE-PROTEIN GLUES

CASEIN GLUES

Casein glues have only recently been used in the woodworking industry in the United States, although they have been known here since about 1873 [4] and have been used in Europe in bookbinding and cabinetwork for a much longer time. The World War greatly stimulated the use of these glues in America. When airplanes were first manufactured in large numbers, requiring water-resistant members of plywood and laminated construction, a wide and important field was opened for casein glue, and its use has since expanded in other industries.

Casein glues are made by mixing water and certain chemicals with casein, which is made from milk. They are often referred to as glue cements because when allowed to set they become entirely different in properties from the original mixture and most of them can not be redissolved by water.

The main advantage of casein glues is their high water resistance or ability to retain strength when wet. Casein glues are mixed and used cold. The better casein glues produce joints which are adequate in strength for most woodworking purposes. At present,

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[4] Probably the first specific description of a casein glue in the American literature occurs in the following: ROSS, J. H., and ROSS, C. D. PROCESSES OF PREPARING GLUE. (U. S. PATENT NO. 183024.) U. S. Patent Office, Off. Gaz., 10: 598. 1876. (Filed August 11, 1873.)

however, many manufacturers are directing their efforts toward making additional casein glues that shall be cheap, easy to handle, and otherwise advantageous, even at the expense of water resistance.

Among the disadvantages of casein glues for certain uses are their dulling effect on tools, their tendency to discolor certain woods, their relative short working life, and their high viscosity. All strong glues dull the knives of woodworking machines to some extent in machining a joint after gluing. Many highly water-resistant casein glues are especially bad in this respect. The dulling effect of a glue line on knives is also affected by the thickness of the glue film in the joint (*9*). The tendency to stain has been reduced in the case of some special casein glues, but experience with such glues indicates that the properties of nonstaining and high water resistance have not yet been combined in the same casein glue. Means of increasing the working life of casein glues is discussed later on this page. The high viscosity of casein glues makes them inconvenient to spread by hand unless a special brush is used or the glue is mixed thinner than is customary.

Casein, the principal ingredient of casein glue, is the prepared curd of milk. When obtained as the product of natural souring it is known as self-soured or lactic-acid casein. It may also be precipitated from milk by sulphuric and hydrochloric acids. The general method of preparation is to remove the acid and other impurities from the curd by washing and then to dry and grind it fine enough to pass through a No. 20-mesh or finer sieve. Variations in details of the process yield caseins of somewhat different properties (*16*).

Casein of the very highest commercial grade is not essential for glue making. It does not follow, however, that a decidely inferior casein will yield a high-grade glue. Some of the desirable properties of a casein for use in glue making are low fat and acid content, freedom from sour odor, larvæ, burnt or discolored particles, or marked impurities of any kind. The ash content of the casein is of importance, since it is a fairly good measure of the amount of water which must be used in preparing a glue of suitable consistency (*15*). It is considered safest to use a casein of medium ash content and medium water requirement for the highest grade of casein glue.

Besides casein and water, a third principal ingredient of most casein glues is hydrated lime, which reacts with the casein to form a highly water-resistant compound. A properly proportioned mixture of these three substances will give a strong, water-resisting glue. Such a glue, however, will remain in workable condition only a short time.

To lengthen the working life of the glue a fourth ingredient is added. Trisodium phosphate, sodium fluoride, sodium silicate, sodium hydroxide, copper sulphate, and copper chloride have been used for this purpose in patented formulas.

Some of the above chemicals have additional desirable properties; for example, the copper chloride also has the property of giving the glue a high water resistance. In addition to the above, various other chemicals have also been added to casein glues to produce improved glues (*11*).

Casein glues are classified as "prepared" and "wet-mix." Prepared glues can be bought in the form of a powder containing all the dry ingredients and requiring only to be mixed with water. Wet-mix glues are made up by the user from the several raw materials. A number of formulas for wet-mix glues have been developed by the Forest Products Laboratory,[5] and some have been published. The use of prepared glues requires less technical skill than the use of wet-mix glues, although a standard procedure for the wet-mix glues can be acquired with a little practice.

SOY-BEAN AND PEANUT-MEAL GLUES

Vegetable-protein glues originated on the Pacific coast and are used extensively in the plywood industry of that section. Of this large class of protein materials the soy bean (*40*) and the peanut meal are typical representatives. Their glue-making properties are more analogous to those of casein glue than to those of starch glue. In preparation and use, the good-quality soy-bean and peanut-meal glues are similar to the casein glues. They are cheap, but have not yet proved to be entirely satisfactory for gluing all kinds of wood.

VEGETABLE GLUES

"Vegetable glue" is a term applied in the woodworking trades exclusively to glue made from starch. The properties of vegetable glues and the way in which they are manufactured clearly differentiate them from the starch adhesives classified as pastes. Vegetable glues have been used extensively in recent years because they make strong joints, are cheap, can be used cold, and can be kept free from decomposition and in good working condition for many days. They are impracticable for some uses becauses they are extremely viscous, lack water resistance,[6] stain certain woods, and set relatively slowly.[7]

Vegetable glues are made either from raw starch (*29*) or from processed starch. Some methods of manufacture of vegetable glue are patented.[8] These patented methods differ mainly in that chemicals added to the raw starch either remain in the glue when sold or are allowed to "process" the glue and are then removed by washing or neutralizing. Vegetable glue may also be made from raw starch without the addition of chemicals.

The principal raw material used in making vegetable glues is cassava starch, which is obtained from the roots of cassava, a tropical plant. This starch in edible form is more familiarly known as tapioca. Potato, corn, wheat, and rice starches can also be, and to some extent probably are, used as the bases of vegetable glues. Of these, potato starch is the most favored.

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[5] Two formulas, developed at the Forest Products Laboratory and covered by United States patents Nos. 1456842 and 1291696, have been dedicated to the people of the United States or assigned to the United States of America. (See Appendix.) BUTTERMAN, S. PROCESS OF MANUFACTURING WATERPROOF ADHESIVES. (U. S. PATENT NO. 1291696.) U. S. Patent Office, Off. Gaz. 258: 354. 1919. ——— and COOPERRIDER, C. K. PROCESS OF MANUFACTURING WATERPROOF ADHESIVES. (U. S. PATENT NO. 1456842.) U. S. Patent Office, Off. Gaz. 310: 1129. 1923.

[6] Efforts have been made by private individuals to produce water-resistant starch glue, and some success has been reported along this line, but as yet no such glue has been offered on the market.

[7] A vegetable glue said to be quick setting is now produced by one of the large vegetable-glue manufacturers.

[8] BLOEDE, V. G. PROCESS OF MANUFACTURING VEGETABLE GLUE. (U. S. PATENT NO. 1,357,310.) U. S. Patent Office, Off. Gaz. 280: 21. 1920. PERKINS, F. G. GLUE AND METHOD OF MAKING THE SAME. (U. S. PATENT NO. 1,020,655.) U. S. Patent Office, Off. Gaz. 176: 619. 1912. ——— PROCESS FOR MAKING GLUE. (U. S. PATENT NO. 1,020,656.) U. S. Patent Office, Off. Gaz. 176: 619–620. 1912.

A properly mixed vegetable glue is translucent, colorless or of a brownish shade, viscous, and usually tacky. Caustic soda is usually added to vegetable glues by the user to make them stringy and less viscous. The caustic soda also lengthens the working life of the glue, but it discolors certain woods and may therefore be objectionable.

BLOOD-ALBUMIN GLUES

The use of blood-albumin glues is not extensive in the United States but is more common in European and Asiatic countries.

Blood albumin, a slaughterhouse by-product, has the property of coagulating and setting firmly when heated to a temperature of about 160° F., after which it shows marked resistance to the softening effect of water. This characteristic makes it a desirable glue for use in the manufacture of highly water-resistant plywood. The chief drawbacks to the use of most blood glues in woodworking are the necessity for hot pressing, which requires expensive machinery and considerable handling; their usually low dry strength; and the fact that they can not be marketed in a dry-mixed form ready for the addition of water. However, recent tests have shown that a highly water-resistant and moderately strong blood glue can be prepared which does not require hot pressing. (See Appendix.) It has not yet been possible to secure as uniformly good results by cold pressing as by hot pressing the glue.

The blood of cattle is generally used for glue making. The albumin is separated from the other substances of the blood and then dried at a temperature below its coagulating point. It may vary in color from dark red to very light red or even be almost colorless, according to the manufacturing process. The dark albumin is lower in price and is generally used in glue making.

Various formulas used in mixing blood glues are patented[9] and others are held as trade secrets. Alkalies such as hydrated lime or caustic soda are used in formulas to increase the adhesiveness of the glue. If a sufficient quantity of alkali is added, partial coagulation of the albumin occurs, and a jellylike mass results. By a proper control of alkalinity, temperature, and stirring, a large proportion of water can be added without breaking down the jelly form of the glue.[10] Blood-albumin glues with the highest proportions of water, however, are often lacking in strength.

GLUE TESTS

Whether or not tests of glue are necessary must be determined by the user, taking into account the importance or volume of work to be done. Sampling and testing of large consignments to determine whether the purchased glue conforms with specifications are advisable.

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[9] Two formulas, developed at the Forest Products Laboratory and patented by it for the benefit of the public are covered under United States patents Nos. 1,329,599 and 1,459,541. (See appendix.) HENNING, S. B. GLUE AND MANUFACTURING SAME. (U. S. PATENT NO. 1,329,599.) U. S. Patent Office, Off. Gaz. 271 : 48. 1920. LINDAUER, A. C. BLOOD-ALBUMIN GLUE. (U. S. PATENT NO. 1,459,541.) U. S. Patent Office, Off. Gaz. 311 : 669. 1923.

[10] ALLEN, C. B. WATERPROOF CEMENT. (U. S. PATENT NO. 1,231,468.) U. S. Patent Office, Off. Gaz. 239 : 1160. 1917.

The grade of an animal glue is generally determined by the combined results of jelly strength and viscosity.[11] Other tests, such as for grease, foam, odor, and acidity or alkalinity, are of less importance, but nevertheless significant for animal glues used in woodworking.[12] Mechanical tests of specimens of dried glue or glue coated or impregnated material have been used to some extent (*4*, *5*, *23*, *28*, *34*), but their value is questionable as a means for determining the suitability of a glue for woodworking. Wood-joint tests, although commonly made, are also not a reliable means of judging the grade of an animal glue. Unfortunately, joint tests are the only tests yet available for determining the suitableness of blood-albumin, casein, vegetable-protein, and starch glues for use in woodworking.

A description of the principal methods and apparatus used for testing glues is given in the appendix.

PREPARATION OF GLUES FOR USE

A standard procedure should be adopted in preparing glues for use. This involves such details as the amount of water to be added, method of combining glue and water, and time of mixing. A standard procedure gives a more uniform mixture and avoids too much reliance on the individuals who do the mixing. Clean, cold water should be used with all glues. The quantity of dry materials and water should be accurately determined by weight. The correct proportions of glue and water vary for different kinds of glues, woods, types of joints, and conditions under which the gluing is done. (See pp. 11, 12, and 13.) For most glues used in woodworking the proper amount of water varies from 1½ to 3 parts to 1 part of dry glue by weight. With a given glue the amount of water used should be less where quick setting is desired. The amount of water used should also be less with porous woods, end-grain surfaces (p. 42 and Table 7), or where high joint strength is desired, than with nonporous woods, side-grain surfaces, or where high strength is not required. A glue mixture with a large proportion of water gives a large spread and is in a satisfactory condition for pressing a long time after the spreading. The mixing should be done in such a way as to produce a solution of uniform consistency relatively free from air bubbles and particles of undissolved material.

PREPARING ANIMAL GLUES

In preparing animal glue the grade largely determines the quantity of water to be added. A glue grading No. 12 in the National Association of Glue Manufacturers scale (p. 15) requires about 2¼ parts of water to 1 part of dry glue by weight for high-quality joint work and about 3 parts of water to 1 part of dry glue for veneer

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[11] Domestic glues are commonly graded upon both jelly strength and viscosity, but imported glues may be graded on other bases. According to Bogue (*6*), "In Germany the viscosity test proposed by Fels, made by the use of the Engler viscosimeter at 35° C., seems to be in greatest favor. In Italy a combination of viscosity and melting point is used. In France and England the viscosity test and the melting-point test by Cambon's fusiometer are employed."

[12] Definite specifications covering these tests are given by the Federal Specification Board, Washington, D. C., for an animal glue suitable for high-grade wood-joint work.

gluing. For these same two classes of work the ratio of water to dry glue for a glue grading No. 6 is about 1½ to 1 and 2 to 1, respectively.

As the water is added to the dry animal glue the mixture should be stirred thoroughly. The mixture should then stand in a cool place until the glue is completely water-soaked. The softened mixture should then be melted. Shredded glue will soften in a few minutes; ground glue in an hour or less; and caked glue will sometimes take several hours, according to the size of the cakes. Of the many types of melting pots in use, those in which the glue flows away as soon as melted or in which the temperature of the mixture can be accurately controlled are preferable.

The temperature at which animal glue is kept liquid has much to do with its quality. A temperature of 140° F. is the most desirable. It is not usually practicable, however, to maintain exactly this temperature when commercial glue pots are used. In any event a temperature range between 140° and 150° should not be exceeded. At temperatures lower than 140°, decomposition of the glue caused by bacteria or other microorganisms may set in, and at temperatures higher than 140°, the deterioration of the glue from chemical action is hastened. Numerous tests have proved that both high temperatures and long-continued heating, even at temperatures lower than 140°, reduce the strength of animal glue.[13]

RECOMMENDED PROCEDURE FOR FACTORY OPERATIONS

In factories where the same grade of glue is used in various parts of the plant it is good practice to mix and melt the glue at a central heater. (Pl. 1, A.) The melted glue can then be distributed in small lots over the plant or run off into pans and allowed to cool to a jelly. In the jelly form glue does not deteriorate quickly if kept at temperatures ranging from 40° to 50° F., and at these temperatures it may be kept throughout the day. In the jelly form, glue can be distributed in the quantities desired and can be remelted in a bench glue pot at the location where it is needed. If the custom of the plant is to keep the stock of melted glue warm, only a few hours' supply should be melted at a time. The glue pots, pans, and central heater should be thoroughly cleaned each day. Glues remaining

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[13] At the Forest Products Laboratory solutions of a high-grade joint glue and a veneer-grade glue were heated for 48 hours at 104°, 140°, and 176° F., and samples were tested every few hours for strength and viscosity. The deterioration due to heating at all three temperatures was evident in both viscosity and joint-strength tests. In the case of the joint glue a marked decrease occurred in both viscosity and joint strength and at about the same rate. With the veneer glue the loss in joint strength appeared more pronounced than the loss in viscosity. The average shearing strength of joints glued with the high-grade glue decreased about 20 per cent on heating the glue solution for 7 hours at 176°. Under exactly the same conditions the average joint strength of the veneer-grade glue decreased about 35 per cent. The greatest loss in strength and viscosity occurred at 176°. In the solutions kept at 104° there was a sudden drop at the end of 31 hours of heating in the strength of joints made with the high-grade glue, owing possibly to a combination of microorganic and chemical action. The veneer-glue joints showed a pronounced but more gradual decrease at that temperature. The most favorable of the three temperatures tried was 140°, but even at that temperature an appreciable weakening in strength of both glues was noted at the end of 7 hours, and a greater loss in strength after longer heating. Bogue (*6*), after heating a 1 to 2½ mixture at 176°, found that "the value of the glue dropped approximately one grade for each two hours of heating, or from a very high to a very low hide (animal) grade in 12 hours. In actual figures the loss in (joint) strength averaged about 85 pounds per square inch per hour, or about 1,000 pounds per square inch in the 12 hours." Bogue's results expressed differently give a loss in 12 hours of 33 per cent of the original strength. Linder and Frost (*32*) found a decrease in strength of from about 30 to 45 per cent on heating a glue solution for 20 hours at 150°.

unused should be discarded or kept in a refrigerator to be used subsequently only where a lower grade will suffice.

The temperature of the glue is difficult to control at the workbench without some automatic temperature regulator. Electrical glue pots that furnish a moderate, steady supply of heat or that are equipped with a thermostatic control are now in use. It is best to use pots which keep the glue within the recommended temperature range from 140° to 150° F.

Many users are firm in the belief that animal glue must be boiled before it is ready for use, although the contrary has repeatedly been proven by tests. This erroneous opinion is apparently founded on the fact that when a glue is "cooked," water is evaporated and the viscosity of the solution is increased. A thick consistency makes up to some extent for deterioration in quality, and as a result good joints are sometimes made with glue that has been boiled. If, however, water were added to make up for that lost by evaporation, the lowering in grade owing to the boiling would quickly become apparent. The solution would become thinner and thinner as boiling progressed, and decidedly inferior joints would result from the use of such a glue. When the loss of water by evaporation is not replaced there is a decrease in the volume of the glue mixture and hence a costly decrease in the covering capacity or spread of the glue.

DETERIORATION OF ANIMAL GLUE CAUSED BY MICROORGANISMS

Decomposition by bacteria is a well-known cause of serious trouble with animal glue. The bacterial action is usually accompanied by a characteristic offensive odor and quickly deteriorates the glue. Decomposition takes place rapidly at high room temperatures, and "sweet" glue in contact with infected glue soon becomes "sour." The utmost cleanliness should therefore be the rule in handling and using animal glue.

PREPARING VEGETABLE GLUES

Vegetable (starch) glue is prepared by three different methods. In all three the dry glue is first mixed with cold water and stirred until of a uniform consistency. On account of the high viscosity of the mixture, mechanical stirring is a practical necessity. One of the several types of mixers used for mechanical stirring is shown in Plate 1, B. The proportions of water and dry glue used in all three methods vary according to manufacturers' directions from 1½ parts of water to 1 part by weight of dry glue, to 4¼ parts of water to 1 part by weight of dry glue, depending upon the particular kind of glue and the type of work for which it is to be used. The two chief causes of this wide variation in proportions of water and glue are differences in the starches used and in the methods of processing. By the first method of preparation, caustic soda equal to about 3 per cent by weight of the dry glue is dissolved in a small amount of cold water and then slowly stirred into the water and glue mixture. The resulting mixture is then heated to the temperature recommended by the glue manufacturer. While heating, the mixture should be constantly stirred. After the proper heating and stirring, the mixture changes into a viscous and translucent mass. The temperature must be carefully controlled at all times, as excessive heat will caramelize the starch and thus greatly reduce the adhesiveness of the glue. For this reason a steamjacketed heater is generally used. In the second method of preparation 6 per cent or more of caustic is used, and with thorough stirring the caustic itself heats and agglutinates the starch to the desired consistency. In the third method of preparation, the starch and the water are mixed without caustic soda, and the conversion of the starch into glue is accomplished by the action of external heat. The mixing process for this method ordinarily requires an hour. The caustic-free glue is not as stringy as the glue made by the first two methods and has a shorter working life. It is therefore not considered as satisfactory as the caustic glues for some purposes, but it is useful where the staining effect of caustic must be avoided.

After being prepared by one of the methods described, the glue is allowed to cool. It is then ready for use and may be run off into a spreader or storage vat. Vegetable glues do not deteriorate rapidly and may be kept for several days without apparent loss in strength. However, chiefly on account of evaporation they do change slowly in viscosity and workability. After standing several days caustic-free glues become appreciably thicker, whereas glues with a high percentage of caustic become thinner.

PREPARING CASEIN GLUES

Casein glues must not be heated at any stage of mixing. Mixing by hand is laborious and often unsatisfactory. A dough mixer of the type illustrated in Plate 1, C is one of several machines which may be used satisfactorily for mixing casein glue. The requirements of a satisfactory mixer for casein glues are that it shall agitate the mass thoroughly, that the mixing bowl shall be made of a metal that does not corrode rapidly from the action of alkali, and that the bowl shall be readily detachable for cleaning.

Mixers, spreaders, and other equipment used with casein glue should be thoroughly cleaned at regular intervals to prevent deterioration of the glue and the inclusion of pieces of dried glue in freshly prepared batches. A thorough cleaning at least once every working day is therefore desirable.

A "prepared" casein glue is mixed by simply stirring the prepared dry glue into water. Most glues require about 2 parts of water to 1 part by weight of dry glue. An additive or subtractive variation of 10 per cent in the amount of water is allowable for different kinds of work. The water should be poured into the bowl of the mixer first and the glue sprinkled or sifted in slowly while the paddle of the mixer is at high speed (100 to 120 revolutions per minute). Care should be taken that large lumps do not form. After the dry glue has all been added, the stirring is usually continued at half speed until a smooth thoroughly dissolved mixture of even consistency is produced. This ordinarily occurs in 15 to 30 minutes. With a few glues the dry powder is mixed with the water and then allowed to stand, without agitation, until the materials are dissolved.

A "wet-mix" casein glue is prepared by mixing all of the separate ingredients at the time of use. The raw casein is first stirred with the water. If it is then allowed to stand and absorb water, it will dissolve more readily under the influence of an alkali, such as caustic soda, which is next added.[14] Materials that are needed to give the glue an adequate working life or other special properties are put in last, and the mixture is stirred until a smooth glue is obtained. Stirring for 15 to 30 minutes usually suffices. A number of formulas for wet-mix glues have been developed at the Forest Products Laboratory some of which, with special directions, are included in the appendix.

The working life of mixed casein glues may vary from less than an hour to several days, according to the formula used. Most casein glues become noticeably thicker on standing at room temperatures, and the quality of joints made with such glues appears to be unaffected so long as they can be spread satisfactorily on the wood. Casein glues that remain liquid for a day frequently become thinner, which generally indicates a deterioriation of the mixture. Glues that have thinned appreciably should therefore be used with caution. Glue mixtures that will remain liquid, even though used just after mixing, do not produce joints of the highest water resistance.

PREPARING BLOOD-ALBUMIN GLUES

Blood-albumin glues are prepared by combining the individual raw materials at the time of mixing. Dried soluble albumin is generally used in the preparation of blood glues. The proportion of water and other materials added varies greatly according to the formula used and the consistency desired for the work at hand. Blood glues are generally prepared by traditional and undivulged processes. Two blood glue formulas developed at the Forest Products Laboratory, with detailed directions for mixing, are given in the appendix.

In mixing blood-albumin glues cold water should be added to the albumin. The albumin should be allowed to soak an hour or more before the other ingredients are added. Even after this period of soaking a certain amount of insoluble material will remain, and, if excessive, should be strained out. Other ingredients are then added according to formula, and the whole is stirred until a uniform glue is produced.

The working life of blood glues varies considerably with the amount of ammonia, lime, caustic soda, or other ingredients added to the dried albumin. Glues can easily be mixed which have a working life of from several hours to several days. As with other glues made from animal material, precaution should be taken to prevent decomposition.

PREPARATION OF WOOD FOR GLUING

DRYING AND CONDITIONING

The moisture content of wood[15] for gluing should be such that when increased by the moisture from the glue it will be as near as practicable to the average moisture content of the finished article. Moisture changes in glued wood induce stresses which favor warping

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[14] Even soaking for a few minutes is helpful, but one-half to one hour is better. Soaking periods of several hours are used to advantage by some manufacturers.

[15] Instructions for determining the moisture content of wood are given in U. S. Dept. Agr. Bul. 1136, entitled "Kiln-Drying Handbook," by Rolf Thelen (*50*), and in other publications of the Forest Products Laboratory.

and checking. These stresses reduce the strength of glued joints and should therefore be avoided as far as possible.

The range of moisture content of dry wood in service commonly varies, depending mainly upon the humidity to which the wood is exposed, from 4 per cent to 15 per cent or more. The wood in a chair may have as low as 4 per cent moisture in a heated building in winter and as high as 10 per cent moisture in the same room in the summer. The average moisture content of wood in heated buildings is about 7 per cent for the year. Dry wood out of doors has an average of about 12 per cent moisture throughout a large part of the United States but will average less in areas of low humidity and more in areas of high humidity.

The amount of moisture added to wood in gluing varies from less than 1 per cent in lumber of 1 inch thickness to 45 per cent in thin plywood where the amount of wood is small in proportion to the amount of glue. The thickness of the wood, the number of plies, the density of the wood, the glue mixture, and the quantity of glue spread all affect the increase in moisture content of the wood when glued (p. 30).

Thin veneer, even if dried entirely free of moisture, will take up so much moisture from the wet glue that its moisture content will become too high for the finished article and must be reduced. Moisture-free veneer is easily split or cracked, so that great care must be used in handling it preceding the gluing operation. It also very quickly reabsorbs moisture during this handling. Therefore, it is not practicable to dry it below 2 or 3 per cent moisture content. Furthermore, experience has shown that a moisture content of 5 per cent or less in veneer at the time of gluing is satisfactory for furniture and similar uses. Lumber with a moisture content of 5 or 6 per cent is satisfactory for gluing into furniture and similar uses. Lumber for outdoor purposes, however, should generally contain about 11 per cent of moisture before gluing. The moisture added in gluing will then bring the total moisture to about 12 per cent.

The manufacturer shipping glued articles to various parts of the country and making products for various uses can not provide for all the moisture variations to be met in service. He must standardize his operations, and he can therefore aim at approximate averages only.

For the best results in gluing it is also necessary to have the joint free from casehardening and other internal stresses. Internal stresses which are the result of improper drying, are likely to cause warping and checking after the wood is glued. Lumber should therefore be tested for the presence of such stresses before it is removed from the kiln. If found to be casehardened or otherwise stressed, it should be treated to relieve the stresses (*50*).

In drying lumber, although the desired average moisture content may be reached, there will usually be considerable differences in the moisture content of individual boards and even between different parts of the same board. As a result, a conditioning period subsequent to kiln drying or air seasoning is usually desirable to bring the stock to an approximately equal moisture content. This is best accomplished in a storage room in which the temperature and humidity are controlled so as to maintain the desired moisture content.

The lumber is open piled in the storage room and allowed to condition. The time required for conditioning depends upon the species, size, dryness, and method of piling the lumber as well as on the temperature and humidity in the room. A conditioning period of one week is beneficial.

Veneer may be successfully dried in mechanical driers of various types, in dry kilns, or by air drying (*31*). In drying veneer, the internal stresses do not usually cause difficulty. However, when internal stresses do develop they may cause wrinkling, checking, or honeycombing of the veneer. (Pl. 3.) These defects are easily recognizable and can be avoided by improving the drying conditions.

In plywood plants where veneer is cut it is customary to glue it immediately following the drying. For general purposes, veneer is in the proper condition for gluing if it is flat, free from obvious defects, and at a moisture content of 5 per cent or less. Veneer which has been shipped or kept in storage, however, is seldom perfectly flat or dry, so it is customary to redry it just before gluing. This is generally done in hot plate driers in which the veneer remains between the plates until sufficiently dry and flat. In the best practice, the veneer is then placed in piles so that it will keep flat, will cool off before gluing, and will not reabsorb much moisture from the air.

Fancy veneer, such as burl, crotch, or other cross-grained pieces (pl. 2, A), is more likely to wrinkle and check in redrying than straight-grained veneer. Drying on hot plates may ruin this kind of veneer, so it is commonly redried by being placed under pressure between thick boards which are dry and hot. These boards absorb part of the moisture from the veneer without damaging the sheets.

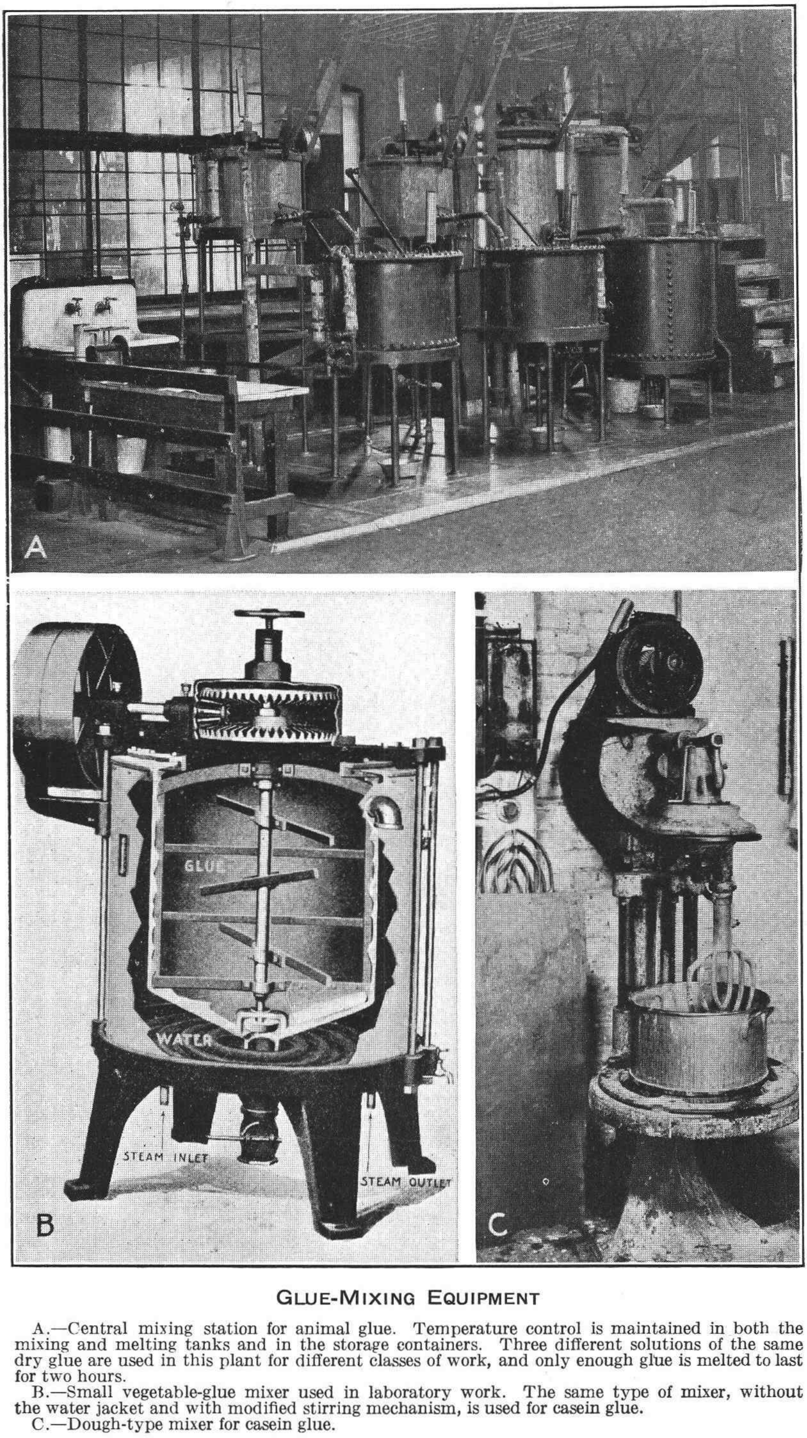
In exceptional cases veneer is glued without first being dried to a low moisture content. Fresh-cut veneer from green logs may be glued with highly viscous water-resistant glue (*45*). By thus avoiding the preliminary drying operation the production cost is reduced and much loss from shrinkage in drying is avoided. On the other hand, there is considerable warping and face checking in drying such plywood and the finished product is usually of low grade.

If water-resistent plywood for aircraft is glued at a moisture content of 12 to 20 per cent, higher strength values are obtained when tested wet than when glued at a low moisture content (*8*). Since aircraft plywood is dried only to about 10 per cent moisture content, warping and checking are not serious. Wet veneer stains more than dry veneer.

MACHINING LUMBER

Careful machining of lumber is necessary in the preparation of wood for gluing. The wood surfaces should be machined smooth, even, and flat. In panel work the pieces should also be machined to a uniform thickess. It is customary to machine the wood just prior to gluing so that the surfaces will not have an opportunity to become distorted from subsequent moisture changes. Where the four sides of a piece are to be glued it is best to glue in two operations and machine just before each operation.

Surfaces made by the saw are usually rougher and more uneven than those made by planers, jointers, or other machines equipped with cutter heads. For this reason sawed surfaces used for cabinet

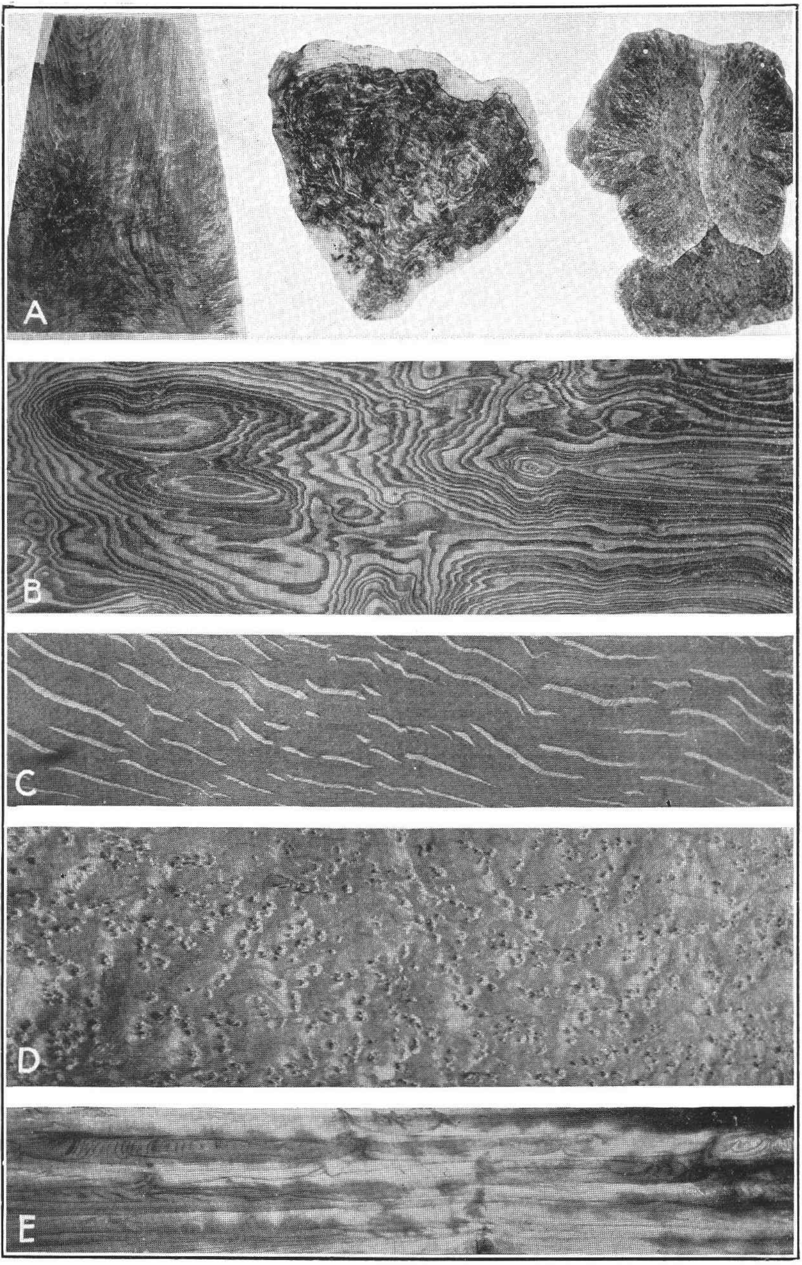


GLUE-MIXING EQUIPMENT

A.—Central mixing station for animal glue. Temperature control is maintained in both the mixing and melting tanks and in the storage containers. Three different solutions of the same dry glue are used in this plant for different classes of work, and only enough glue is melted to last for two hours.

B.—Small vegetable-glue mixer used in laboratory work. The same type of mixer, without the water jacket and with modified stirring mechanism, is used for casein glue.

C.—Dough-type mixer for casein glue.



FIGURED VENEER CUT BY VARIOUS PROCESSES

A.—Walnut veneer cut from a stump and from burls by the half-round process. The tape on the edges of the sheet of stump veneer protects it from splitting.
B.—Rotary-cut ash veneer.
C.—Sawed quartered-oak veneer.
D.—Rotary-cut bird's eye maple veneer.
E.—Sliced red gum veneer.

work joints are not entirely satisfactory where they are to be exposed to view. However, there has recently been a marked improvement in saws used for this purpose so that sawed joints are now being glued which are suitable for certain uses, such as edge joints in core stock. The saving of labor and material effected by gluing surfaces direct from the saw is important, and the practice is likely to increase.

Machine marks caused, for example, by feeding the stock through a planer too fast for the speed of the knives, prevent complete contact of the joint faces when glued. Machine marks in cores of thinly veneered panels are likely to show through the finished surface. Unequal thickness and width which cause unequal distribution of the gluing pressure and usually result in weak joints may be due to the grinding, setting, or wearing of the machine knives. A small variation in the thickness of each piece of wood may cause a large difference when a number of similar pieces are piled and glued in the same order as they come from the planer.

On the theory that roughening and tearing up the surface fibers of wood gives the glue a better chance to adhere, it is customary in many gluing operations to scratch, tooth plane, or sand the surfaces to be joined. This is done by machine or hand and results in tearing or cutting small grooves in the planed surfaces of the wood. However, the Forest Products Laboratory has made many comparative strength tests between smooth and rough surfaces which failed to show that better results are secured with the roughened surfaces, and, furthermore, studies in the penetration of glue into wood have shown the theoretical benefit of the roughened surfaces to be improbable[16] (*21*).

MACHINING SPECIAL TYPES OF JOINTS

The plain, the tongue-and-groove, the circular tongue-and-groove, and the dovetail are four of the most common types of edge joints used in gluing boards into wider pieces. (Fig. 1.) The tongue-and-groove and the dovetail joints possess the theoretical advantage of having larger gluing surfaces than the plain joint. However, plain side-grain joints which are as strong as the wood itself may be glued easily on most woods, and therefore the extra gluing area of the tongue-and-groove and the dovetail joint is not needed. Moreover, the latter joints are more difficult to machine and to fit. Experience has shown that a lack of a perfect fit in tongue-and-groove or dovetail construction often result in joints which are weaker than the plain joints. Furthermore, poorly fitting pieces require a heavier glue line, which result in slower drying and setting of the glue. For fast production, true, close-fitting surfaces are essential. The valuable feature of the tongue-and-groove joint, however, is that the pieces of wood to be glued are held in alignment during the assembling and the subsequent setting of the glue. This makes possible faster clamping and less slipping of parts under pressure, which are advantages so important that some form of tongue-and-groove is

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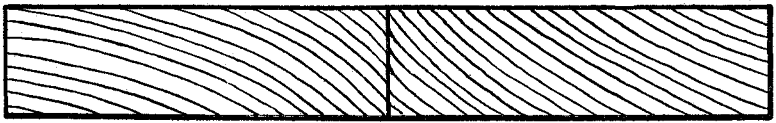
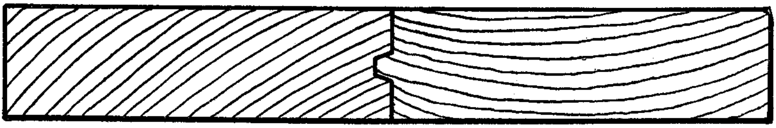
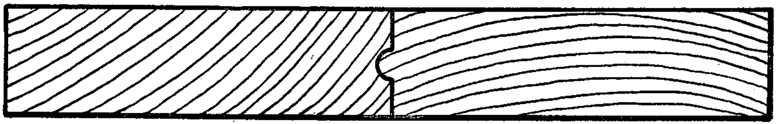
[16] The penetration of the glue into the cell cavities gives a much larger area of contact between glue and wood substance than can possibly result from a roughening of the surfaces.



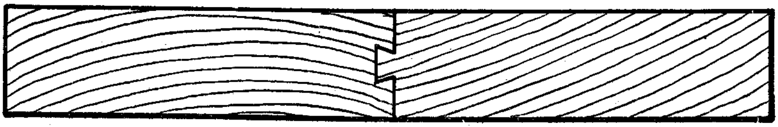
PLAIN



TONGUE AND GROOVE



CIRCULAR TONGUE AND GROOVE



DOVETAIL

FIGURE 1.—Common types of edge joints

used on most commercial edge joints. A shallow tongue-and-groove (one-eighth inch or less) is as useful in this respect as a deeper cut and is less wasteful of lumber.

The difficulties of making a perfect fit of the glued parts are still more pronounced in certain other types of joints. (Fig. 2.) In the serrate, dowel, mortise-and-tenon, dado tongue-and-rabbet, slip, and dovetail joints (fig. 2, C, F, G, H, I, and J) an imperfect fit of the parts results in only partial adhesion in the joints. In most of these joints, complete contact over poorly fit portions can not be obtained under ordinary gluing. Furthermore, pressure is often applied but momentarily in gluing such joints, and the glue does not have sufficient time to set. Careful machining of the parts of irregular-shaped joints is therefore necessary to obtain full strength and durability in service.

PREPARATION OF VENEER FOR GLUING

Veneer for gluing is commonly cut by sawing, slicing, and rotary cutting (*31*, *53*). Most veneer cut by sawing and slicing is glued, but perhaps less than half of the rotary-cut veneer is glued. The total quantity[17] of rotary-cut veneer glued, however, is larger than the combined amount of sawed and sliced stock glued.

Sawed veneer is cut from flitches, usually for the purpose of getting a certain figure or grain. It is produced in long, narrow strips which are of substantially the same quality and appearance on both sides. Being thus equally firm and strong on both sides, alternate pieces may be turned over in matching for figure such as in the faces of veneered panels. Quartered-oak veneer is cut chiefly by this process. Sawed veneer usually ranges in thickness from one-fourth to one-thirtieth of an inch.

Sliced veneer is also cut to obtain a definite figure and is produced in the form of long, narrow strips or sheets. In the slicing process the veneer is sliced from a flitch by moving it against a heavy, stationary knife. The veneer is forced abruptly away from the flitch by the knife, thus causing fine checks or breaks on the knife side of the veneer. (Pl. 3.) The checked side is called the open or loose side, and the other side is called the closed or tight side. The open side is likely to show defects in finishing and therefore should be the glue side whenever possible. In matching face stock where the open side of part of the sheets must be the finish side, the veneer must be well cut. Mahogany, walnut, Spanish cedar, oak, and a few other species are cut by the slicing process. Sliced veneer is cut in thicknesses ranging from about one-sixteenth to one one-hundred-and-twenty-fifth of an inch.

Most rotary-cut veneer is produced in large sheets by revolving the log against a knife, flat-grain veneer being peeled off in a continuous sheet very much like unrolling paper (*31*). The half-round process is used to produce highly figured veneer from stumps, burls, and other irregular parts of logs. (Pl. 2, B.) This process consists of placing off center in a lathe a part of a log and rotary cutting it into small sheets of veneer. All rotary-cut veneer has an open and

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[17] In 1921, 87 per cent of all veneer manufactured was rotary cut, 7.6 per cent sliced, and 5.4 per cent sawed, and in 1923 the percentages were 92, 3.3, and 4.7, respectively (*54*).

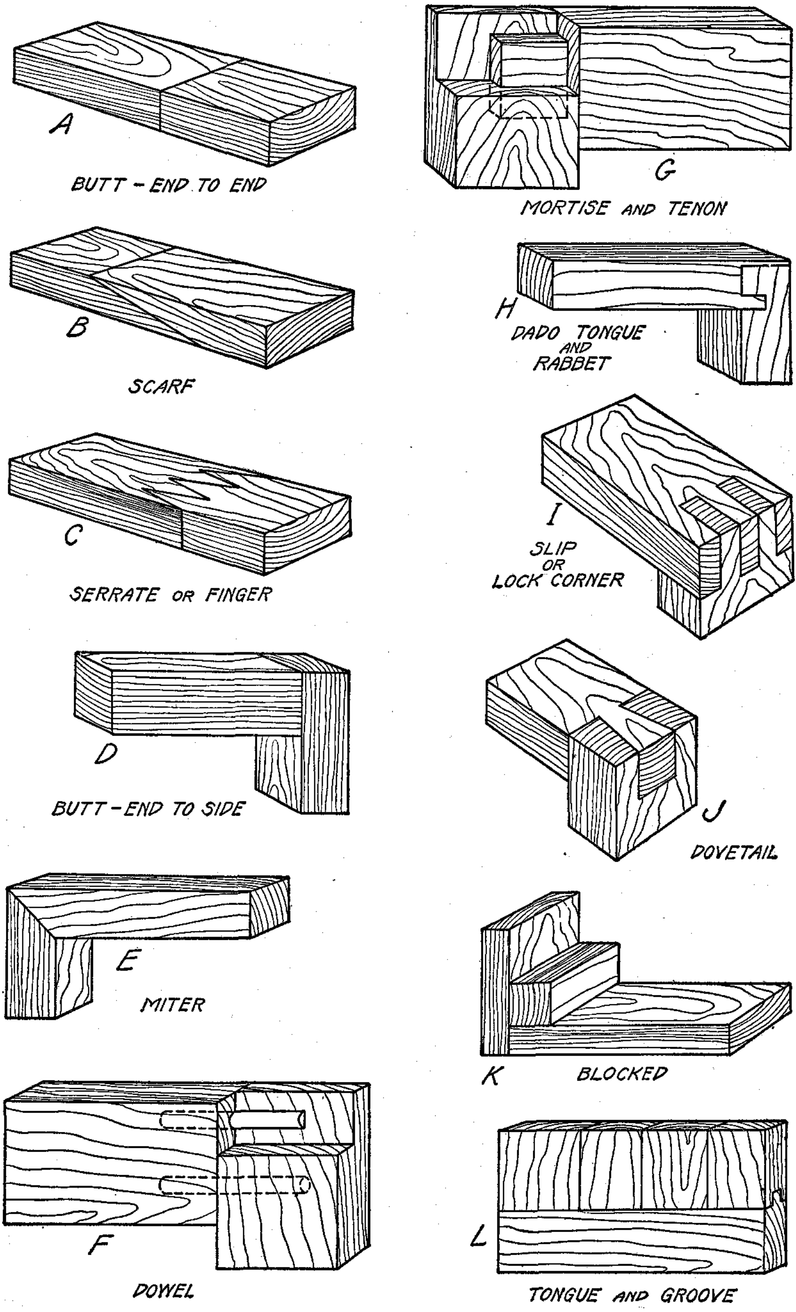

FIGURE 2.—Types of butt-joint construction

a closed side. Most of the important hardwoods and some conifers are cut extensively by this process. Rotary-cut veneer is produced in thicknesses ranging from about three-eighths to one one-hundred-and-tenth of an inch.

Sawed and sliced veneers are used principally for faces in plywood and veneered panels. Rotary-cut veneer is used principally for face stock, for thin cores (five-sixteenths of an inch and less), for cross-banding, and for curved laminated members. (Figs. 3 and 17.) Most veneer, which is glued, ranges in thickness from one-fourth to one thirty-second of an inch. Veneer thinner than one-fortieth of an inch is difficult to handle during the process of gluing because the water in the glue curls the sheets. Ordinarily one-fiftieth of an inch is the minimum thickness of veneer for successful gluing, although some Spanish cedar one one-hundredth of an inch thick is glued for cigar boxes.

Usually surfaces of veneer are somewhat rough and irregular. By careful cutting, however, veneer can be secured that is comparatively smooth and firm on both sides. Veneer is not usually resurfaced before it is glued, and the care with which it is cut is therefore of importance.

In gluing operations where full-sized sheets of veneer are available, the sheets may be glued immediately after drying. Cutting to size is preferably done before the final drying. Cutting after drying allows more opportunity for the veneer to reabsorb moisture from the air. Furthermore, very dry veneer is easily damaged and should therefore be handled as little as possible.

Wherever a face (fig. 3) for a high-grade veneered article is made of two or more pieces of veneer, careful jointing of the edges of the veneer is necessary to make the joints inconspicuous. This type of joint is made by placing the dried veneer in piles of several sheets and then running the piles over a special veneer jointer which makes the individual veneer edges smooth and true. These sheets are then laid in the desired position, and the edges are taped tightly together by taping machines.[18] It is good practice to glue the edges of the veneer together after taping. This is accomplished by folding the two sides back over the tape, coating the exposed edges with glue, and then bringing the edges together again. Laying the freshly glued sheet in a slightly curved form with the tape on the convex side insures that the other side of the joint is held tightly together while the glue sets.

For cores (fig. 3), crossbands, backs, and in low-priced articles even for faces, extreme accuracy in jointing the edges of the veneer is not necessary. Jointing in such cases may therefore be done satisfactorily on a veneer clipper. In certain low-grade panels, where thick veneer cores are used, the veneer sheets are merely laid in position without fastening of any kind. The spaces between the pieces or the lapped edges, which often result, are of minor importance in the grade of panels being manufactured.

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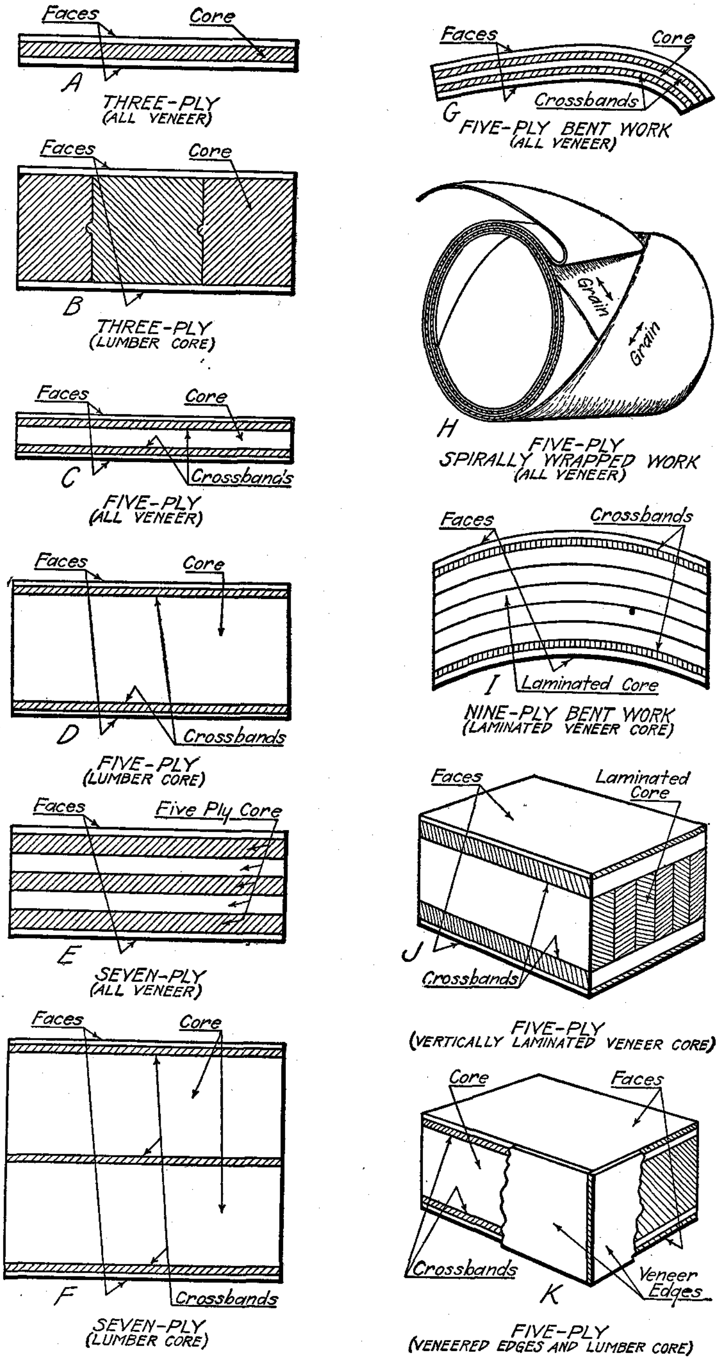
[18] There are devices for edge gluing veneer without the use of tape, but an entirely satisfactory machine for the purpose is not known. Staples are sometimes used to hold the edges of thick veneer together. However, it is difficult to avoid cutting into the staple during subsequent machining. In European countries a device is used for jointing core and crossband stock which cuts a dovetail design in the two edges to be joined and fits them together without glue or tape.



A. THREE-PLY (ALL VENEER)

B. THREE-PLY (LUMBER CORE)

C. FIVE-PLY (ALL VENEER)

D. FIVE-PLY (LUMBER CORE)

E. SEVEN-PLY (ALL VENEER)

F. SEVEN-PLY (LUMBER CORE)

G. FIVE-PLY BENT WORK (ALL VENEER)

H. FIVE-PLY SPIRALLY WRAPPED WORK (ALL VENEER)

I. NINE-PLY BENT WORK (LAMINATED VENEER CORE)

J. FIVE-PLY (VERTICALLY LAMINATED VENEER CORE)

K. FIVE-PLY (VENEERED EDGES AND LUMBER CORE)

FIGURE 3.—Types of plywood and veneered construction

When all the plies of a panel are glued together in one operation the tape used on cores or crossbands must be left in the panel. If a thin, open-mesh, cloth tape is used satisfactory results are obtained by this method. On the other hand, if a thick, solid, paper tape is used and the panel receives a finish later, the crossband tape often causes a raised area, which is objectionable in high-grade panels. The joint at the tape may also be appreciably weaker than elsewhere since its maximum strength is limited by the strength of the tape. Furthermore, the adhesive on the tape may be of relatively low strength. For high-grade work, where solid paper tape is used, it is therefore best to lay core and crossbands (taped side of crossbands out) in one operation, then, after the panels have dried, remove the tape from the crossbands and glue the faces on. Another method, which is sufficient for all but the best finishes, is to lay the taped side of the crossbands next to the core and glue the whole panel in one operation. It is possible for tape even under the crossbands to show through faces of thin veneer. If a panel has a face and a back side, a satisfactory procedure is to use one-piece crossbands under the face and taped crossbands under the back ply.

For panels glued with a water-resistant glue, the glue on any tape which may be left in the panel should also be water-resistant. A perforated cloth tape is generally used for such work upon which a water-resistant glue is spread as the tape is applied to the veneer. The perforations reduce the area to be covered by the tape and thus allow frequent points of direct contact of the glue with the adjacent plies.

Removal of the tape from the glued plies is best accomplished by sanding or machine scraping when the tape is dry. If the tape has been applied with nonwater-resistant glue, it is often moistened and then scraped off by hand. This, however, is liable to permit the joint between the edges of the veneer to open on subsequent drying and thus partially defeat the purpose for which the tape was used. If much water is used in moistening the tape, it may also cause checking in the face veneer.

THE GLUING OPERATION

SPREADING GLUE

To make a satisfactory joint it is important to spread an adequate amount of glue evenly and quickly over the surfaces to be joined. Hand spreading with all but very thick glues is practicable on small or irregular surfaces or where the amount of gluing to be done is not great enough to justify the employment of labor-saving machinery. Machine spreading, on work adaptable to it, is quicker, more uniform, cheaper, and more economical of glue than hand spreading, and for these reasons the greater proportion of all glue used on wood is spread mechanically.

Among the various types of mechanical glue spreaders in successful use are double-roll spreaders (pl. 4) for spreading both sides of flat pieces; single-roll spreaders for spreading one side or edge of flat pieces; perforated plates which rise vertically out of the glue for spreading edge surfaces; machines for squirting glue into dowel holes and onto lock-corner joints; and revolving brushes for spreading it into dovetail joints.

Animal, liquid, thin casein, and liquid-blood glues may be spread by hand with ordinary bristle brushes. However, metal-bristle brushes are more durable for the alkaline casein glues. Generally, mechanical means are required for spreading thick vegetable glue, thick casein glue, and the jelly form of blood glue. Wooden paddles or metal scrapers may, however, be used to spread thick glues on small areas.

Speed in spreading is necessary where glues change rapidly in consistency after being spread, where there are several joints in one construction, or where, as in gluing plywood (figs. 3 and 17), the spread veneer sheets are piled together and pressed at one time. (Pl. 8.) High speed for mechanical spreaders is also desirable for quantity production but the speed must be controlled so as not to whip air into the glue.

Uniform spreading by hand requires great skill, and even mechanical spreaders must be kept in proper adjustment for such spreading. In coating two sides of a piece of wood with glue in a double-roll spreader it is also necessary that the wood be of uniform thickness.

It is safer to spread an excess amount of glue than to spread too little, for if too little is spread the joints may be weak. (F. 41.) More of a thin glue than of a thick glue is absorbed by the wood and is squeezed out under pressure; hence, a heavier spread is required for thin glues. Absorbent woods take up more glue than less absorbent woods and must therefore receive a thicker glue spread. Rough surfaces require more glue than smooth surfaces, and poorly fitted joints more than closely fitted joints.

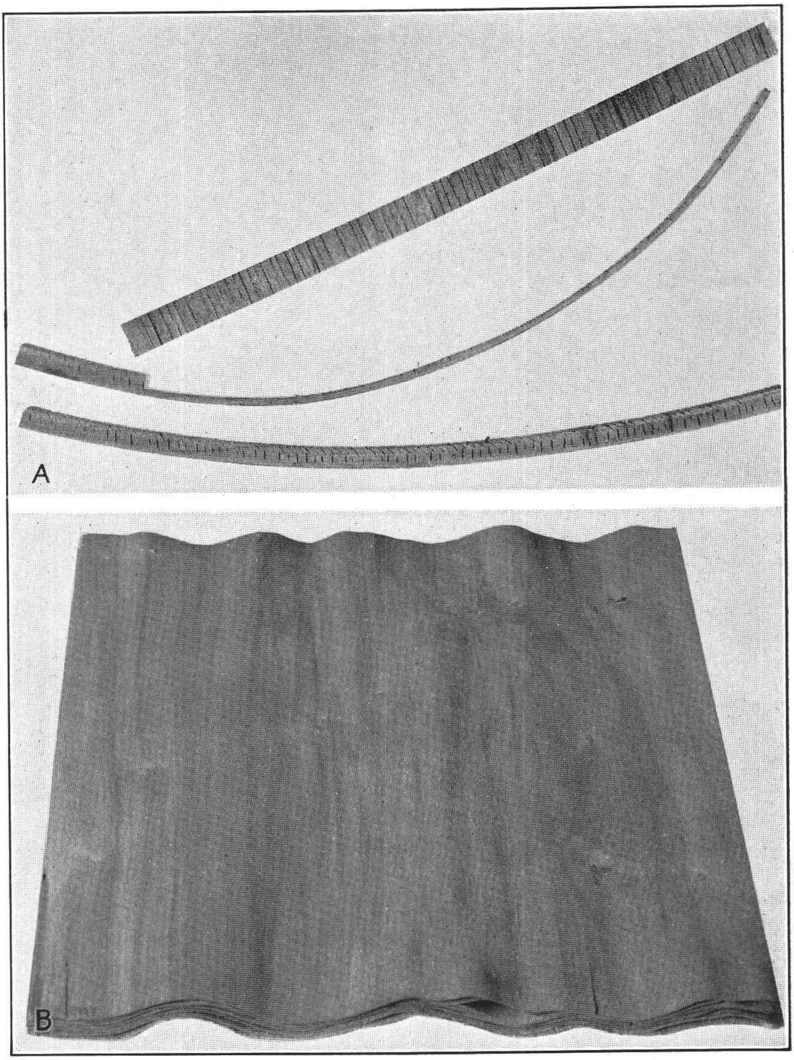
In most commercial gluing only one of the contact faces of a joint is spread (single spreading). However, when precautions are taken to insure strong joints, both faces are sometimes spread (double spreading). Tests at the Forest Products Laboratory using both methods have shown that in gluing flat surfaces there is no significant difference in the strength of joints made by these two methods under good gluing conditions. Under adverse gluing conditions, however, such as when the glue on the wood becomes thick before pressing, double spreading is more reliable.

PRESSING AND CLAMPING

In gluing wood, pressure is required to bring the surfaces of the joint into contact, to force the air and excess glue from the joint, to spread the glue into a thin film of approximately uniform thickness, to force the glue into the wood cells which are adjacent to the glue line, to hold the joint in correct position while the glue sets, and to prevent warping. Mechanical devices (*14*) used in applying pressure to glue joints, a few types of which are shown in Figure 4 and Plates 5, 6, and 7, are therefore necessary in practically all wood gluing.

AMOUNT OF PRESSURE

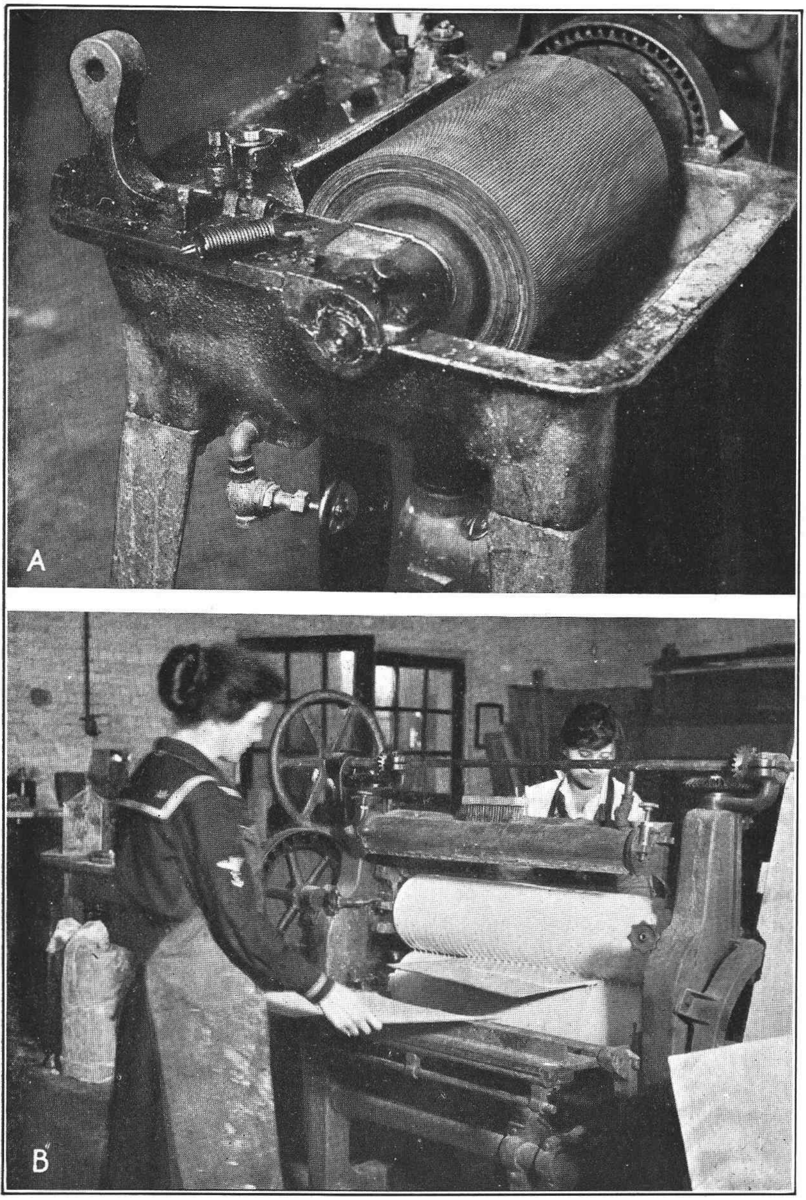
It is possible to make well-glued joints with pressures which range from a few pounds, such as are exerted on rubbed joints, to 1,000 or more pounds per square inch (pp. 33 to 38). It may require as much



DEFECTS DEVELOPED IN DRYING VENEER

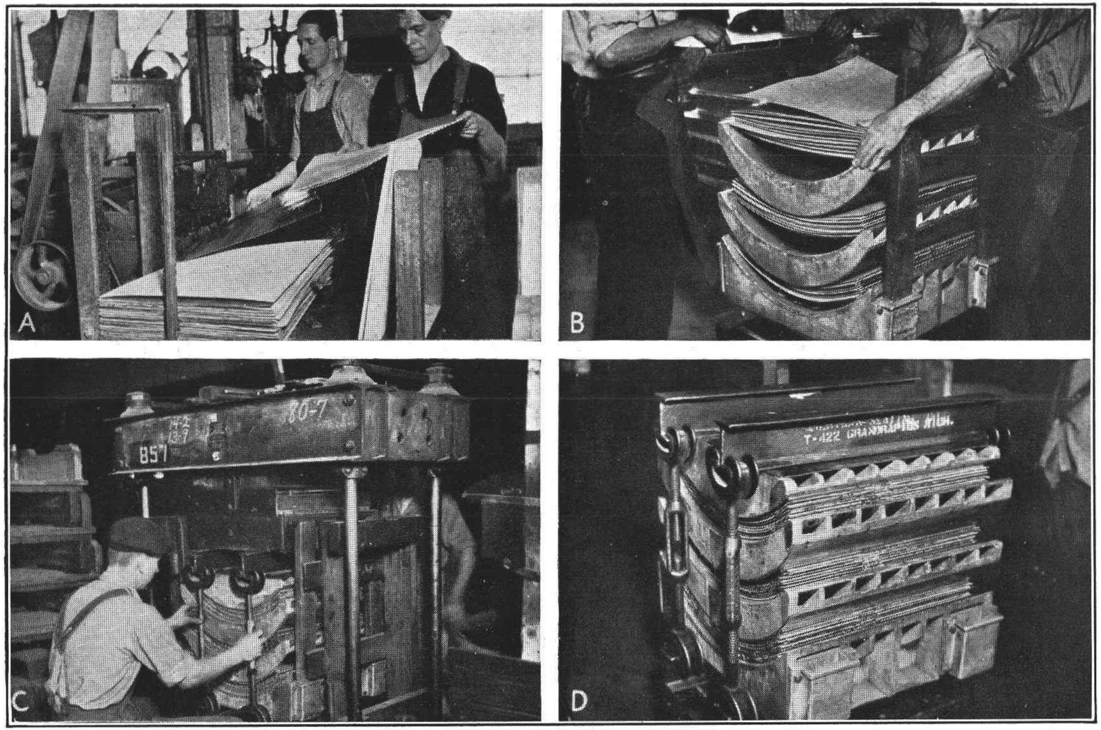
A.—Rotary-cut red gum veneer, five-sixteenths of an inch thick, badly honeycombed in drying. The upper piece, which was sawed out of the middle piece, shows numerous internal checks. The sharp curvature of the connected prong of the middle piece indicates a severely stressed condition. The many oblique checks showing on the upper surface (open side) of the lower piece were developed in cutting the veneer from the log.

B.—End wrinkling produced in veneer by uneven drying.



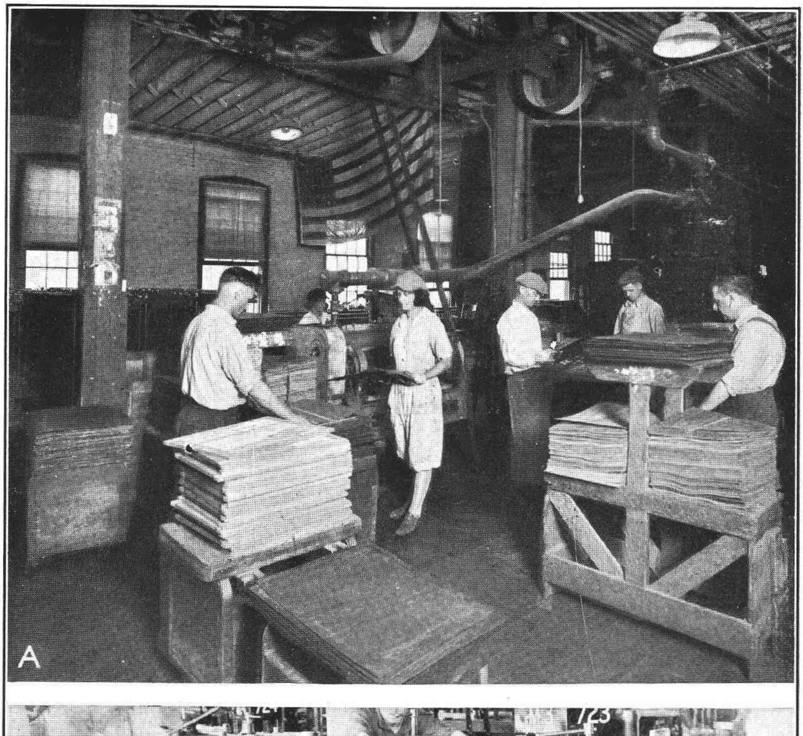
TWO TYPES OF GLUE SPREADERS

A.—Single-roll spreader used chiefly for thick stock.
B.—Double-roll spreader. Veneer fed between the rolls is coated simultaneously on the two sides.



PLYWOOD-SEAT GLUING OPERATION

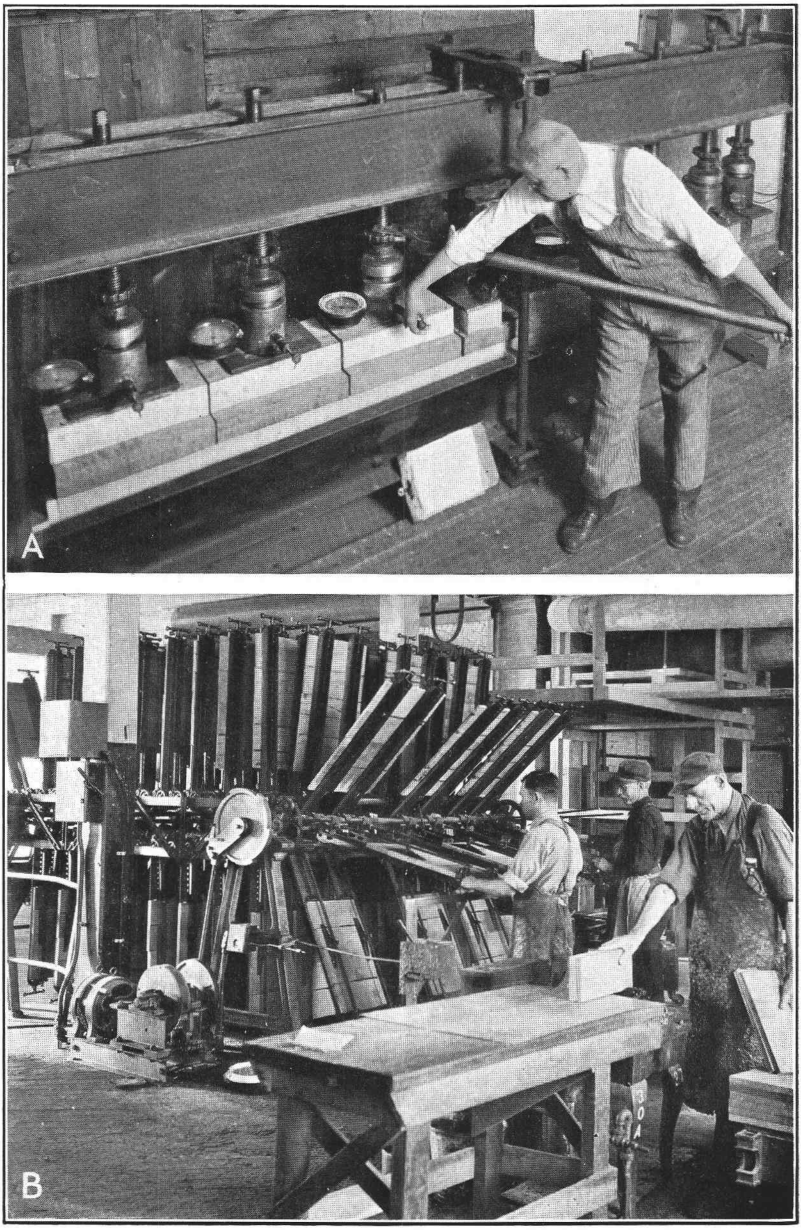
A.—Spreading the glue and laying the veneer.
B.—Placing the assembled stock between curved cauls for pressing.
C.—Pressure applied and retaining clamps being put in position.
D.—The stack of panels held by retaining clamps is allowed to stand several hours for the glue to set.



TWO TYPES OF COMMERCIAL GLUING OPERATIONS

A.—Panel-building operation. This crew is building up simultaneously three stacks of panels from the one spreader. The peripheral speed of spreader rolls is about 150 feet per minute. One stack of panels goes to the press on an average of every two minutes.

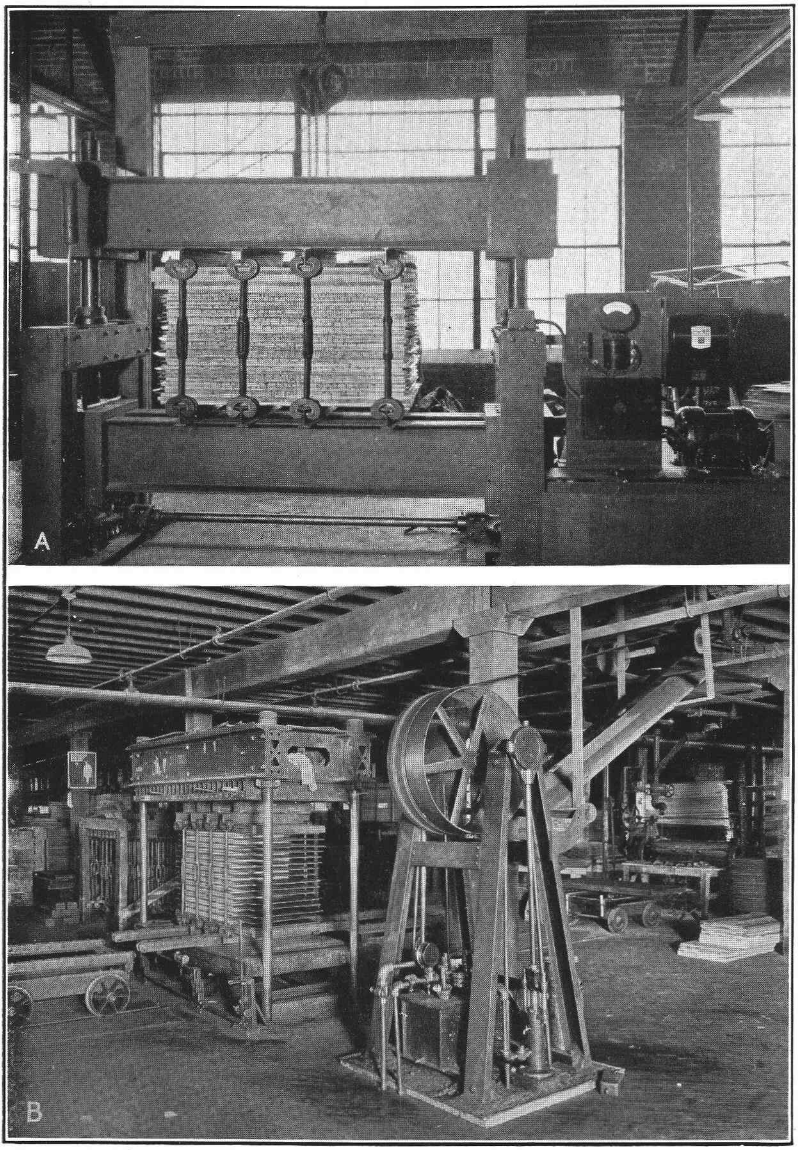
B.—Grand-piano rim-gluing operation. The glue-coated layers of veneer are clamped securely around a central form by means of a series of hand screws bearing on thick cauls. The rims are left in the form until the glue has set.



SCREW-TYPE PRESSES

A.—Large hand-screw press at the Forest Products Laboratory. The instruments under the jackscrews are used to measure the loads. This special equipment was used to study the effect of pressure on the strength of joints in thick stock.

B.—A revolving clamp carrier used in gluing edge joints. The pieces are coated with glue on the edges by a roll-type spreader.



POWER VENEER PRESSES

A.—Electric power press. Pressure is applied by means of a motor and set of gears. The gauge indicates the amount of pressure applied. I beams and retaining clamps are in place and the bundle is ready for removal from the press.

B.—Hydraulic press. Pressure is applied to one platen by means of a piston. The amount of pressure per square inch on the piston is indicated by the gauge. A thin caul is placed upon every other panel in the stack. Bundles of panels are moved from the spreader to the press and away again on trucks.

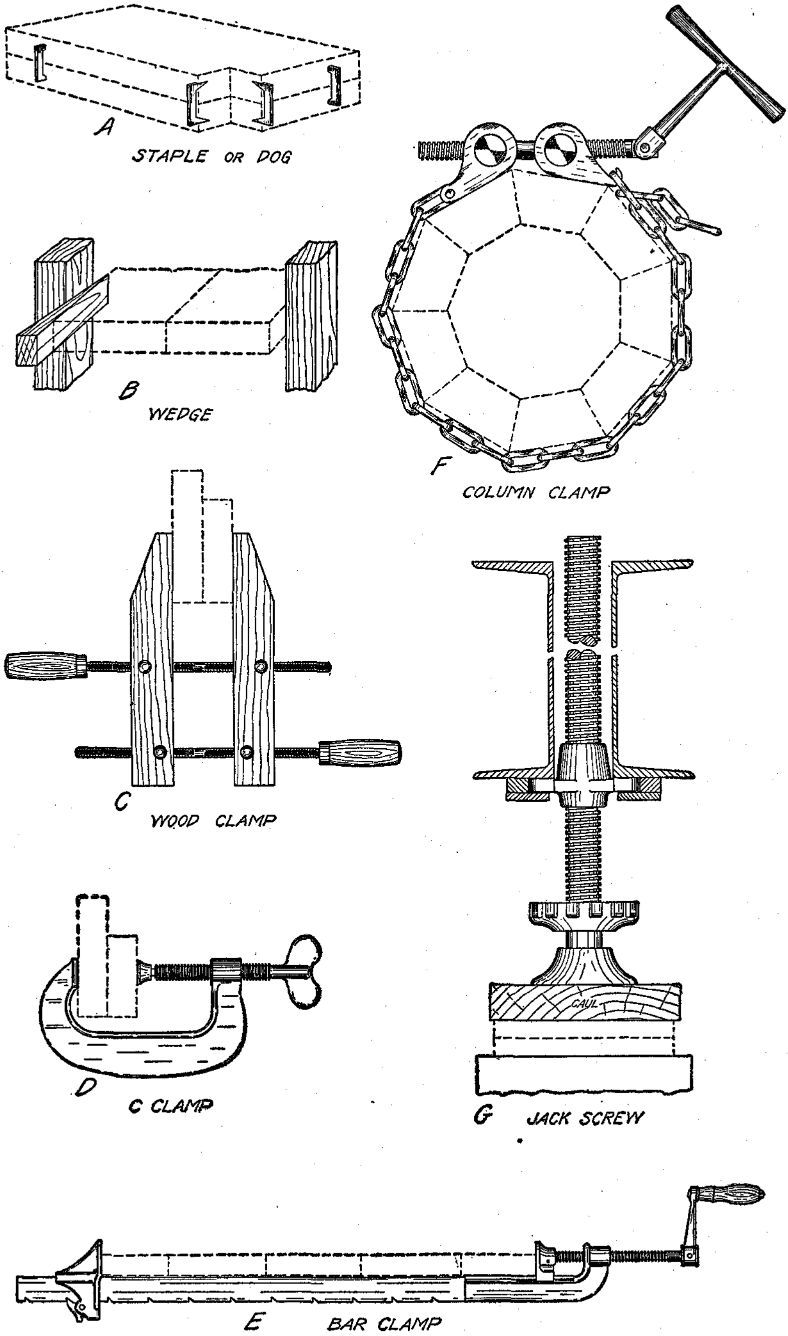


FIGURE 4.—Hand devices used in applying pressure to glue joints

as 50 pounds pressure per square inch before the entire surfaces of warped pieces of thick wood are close enough together to permit the making of satisfactory joints. Some woods, after being wet from the water in the glue, crush at about 200 pounds pressure per square inch. In most commercial gluing operations pressures of 100 to 200 pounds per square inch will give satisfactory joints and will not injure the wood.

In hand-screw clamps and presses the amount of pressure applied is usually unknown to the operator. Fortunately, the range of pressures throughout which good joints may be obtained (p. 34) is so broad that trained operators of screw clamps and presses are usually successful even though they have no accurate knowledge of the amount of pressure they are applying. Satisfactory power presses (pl. 7) are equipped with pressure-indicating devices which enable the operator to adjust the amount of pressure (p. 74) to the size of the joint, the kind of wood, or other gluing conditions.

Efficient use of a power press demands that it shall be continuously available for service. For example, piles of panels are stacked at the glue spreader, then transferred to the press where, as the load is applied, they are quickly bound with I beams and turnbuckles, and then removed from the press. (Pl. 5.) By this method a stack of panels may be pressed every few minutes with one press.

EVEN DISTRIBUTION OF PRESSURE

Pressure should be applied uniformly over the surface of the wood to be glued. This presupposes that the surfaces to be joined are true and fit accurately and that the pieces are of uniform thickness. In order to secure a sufficiently uniform pressure the clamps and the screws must be properly spaced with the bearing surfaces parallel. For the same reason thick cauls should be used under the bearing surfaces when gluing thin pieces such as veneer, and occasional inspections should be made of power presses to insure that the platens are true and parallel. The staple and wedge devices shown in Figure 4, A and B, do not distribute pressure evenly and therefore are not suitable for use on high-grade glued joints.

The cauls generally used on the top and bottom of a stack of glued veneer (pl. 8) should be smooth and of uniform thickness, and, where heavy loads are applied, should be 3 to 4 inches thick. Thinner cauls of wood, metal, or other material may be used at various places throughout the stack to compensate for any irregularities in the stock. In commercial gluing cauls are frequently used with every 5 to 10 panels. Where valuable veneered stock with two good faces is being glued, it is well to use thin cauls alternately with the panels throughout the stack. If the panels have only one good face, the cauls may be at intervals of two panels laid face to the caul. (Pl. 8, B.) Curved cauls are used where the veneer is pressed into curved panels, such as in chair seats. Such cauls are cut out or formed to the desired shape, and the veneer panels are pressed between them. (Pl. 5.) Cauls should be coated with wax, grease, or other suitable substances to keep the glue from adhering to them and also to make them easy to clean. In some operations paper is placed between high-grade veneered panels to prevent the panels from sticking together and to absorb some of the moisture which is added by the glue.

UNDUE DEFLECTION IN PRESSES

Where heavy pressures are applied, such as in gluing veneer, there should be no undue deflection or bending in the presses or in the I beams. The jackscrew of the older types of veneer presses (pl. 7, A) are capable of withstanding 30,000 pounds pressure per screw. An average man on this type of screw using an 18-inch lever may apply a load of from 18,000 to 20,000 pounds. Where several such screws are mounted on one press they may, therefore, cause a large deflection in the press. Loads applied on the first screw may be lessened as subsequent screws are tightened and may, therefore, cause unequal pressure distribution over a part of the joint. Likewise, due to the bending of the I beams unequal pressure may occur in bundles of veneered panels after their removal from the press. Deflection of presses or I beams may be detected by applying straightedges to the suspected member or by pressure-indicating devices placed under the bearing points.

DURATION OF PRESSURE

The length of time that glue joints should be left under pressure depends upon the rate at which the joint gains strength. Except in hot pressing, joints increase in strength primarily as a result of the drying of the glue. The most rapid setting occurs in a warm room when a thin spread of quick-setting glue is applied to thick layers of dry wood. Pressure applied momentarily and then released may give good results with joints made of thick members which fit accurately and which do not change their shape on account of the moisture added by the glue, provided that the joint is not disturbed until the glue has set. Such a condition seldom occurs in commercial operations, so that it is best to retain a pressure until the glue has at least partially set. In edge gluing in cores (fig. 1) a pressure applied for 30 minutes to 1 hour generally gives satisfactory joints. In veneer work (fig. 3) the pressure should be retained on the joint from several hours to a day.

Rate of Setting of Animal, Casein, and Vegetable Glues on Lumber

Forest Products Laboratory tests made to determine the rate at which glued joints gain strength during the pressing and conditioning time show that animal and casein glues set at approximately the same rate when the room and the wood are at a temperature of about 70° F. Figure 5 shows how in thick stock the casein and the animal-glue joints increase in strength with age under the above conditions. The curve indicates that only a small percentage of the final strength of the thick joints exists at the end of one-half to one hour. The final strength of the joint when pressed for such a short period of time is contingent upon careful handling when it is removed from the press and upon a further conditioning period. Tests on similar joints which were pressed for periods of less than two hours and then thoroughly seasoned before being tested show a lower ultimate strength than those kept under pressure for longer periods. However, the lumber joints which were pressed for only one-half to one hour showed sufficient strength after conditioning for most kinds of construction. Nevertheless, where lumber joints of uniformly high strength are required a pressing period of four hours or more is safer practice.

Tests have also been made on lumber joints glued with vegetable glue. The average rate of increase in the strength during the pressing and conditioning time for such joints was appreciably slower than that obtained for the animal and casein joints. On all of the vegetable-glue joints, however, there was a wide variation in the strength of individual specimens tested, so that in some cases the vegetable-glue joints compared favorably in strength with the joints made with animal and casein glues of the same age.

The strength of lumber joints made with animal glue in a warmer room and with heated wood showed a more rapid increase than that indicated in Figure 5. This was apparently the result of the thinner glue line and the faster drying under the warmer conditions. At 70° F. the animal glue thickened quickly, and at the time of pressing was similar in consistency to the casein glue. Heating the wood and gluing in a room of high temperature hasten the drying and setting of the glue, but there is a serious danger of producing joints of lower final strength. This is discussed later under "Control of gluing conditions," page 32.

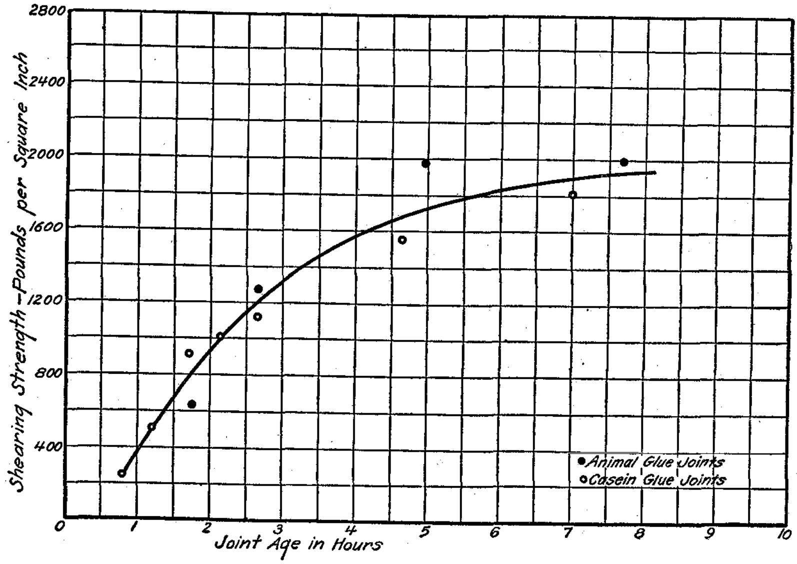


FIGURE 5.—Increase in strength of animal and casein glue joints during the pressing and conditioning time. Tests were made on hard maple of approximately three-fourths of an inch thick and glued into blocks. Gluing room and the wood were both at approximately 70° F.

RATE OF SETTING OF ANIMAL, CASEIN, AND VEGETABLE GLUES ON VENEER

The initial set of the glue in gluing veneer joints is as quick as in the lumber joints, but the rate of approaching the full strength of the joint while in the press is slower. Thin layers of veneer do not absorb rapidly or completely the moisture from the glue and therefore require a long pressing period. Hence, it is customary to leave veneered panels and plywood under pressure for periods of 18 to 24 hours. The exact time of pressing is partially determined by convenience of operation; for example, glued panels of one day's run are left under pressure overnight and removed the succeeding day to free the equipment for a new run. The minimum time for most vegetable-glue panels to remain under pressure is usually about seven hours. However, with casein, animal, and the quicker-setting vegetable glues, the veneered stock sometimes is removed after two to three hours with satisfactory results.

Pressing Time Affects Staining

The alkali present in some glues discolors certain woods. (Table 6.) Removing glued veneer from the press as soon as possible and drying it on stickers reduces the staining, because alkali does not readily penetrate dry veneer.

USE OF HEAT IN PRESSING

The presses used for blood albumin glue are equipped with steam-heated platens.[19] The exact time of pressing depends upon the temperature, upon the thickness of the glued stock, and to some extent upon the kind of wood used. The temperature of the platens ranges from 212° to 300° F., and the corresponding pressure period usually ranges from three minutes to one-half hour. Temperatures near 300° set the glue quickly and give strong water-resistant joints, but they may cause steam blisters to form in the joints and thus ruin a part of the joint. Steam blisters are sometimes prevented by subjecting the panels to the heat necessary to set the glue and then by running cold water through the platens while the panels remain under pressure. This practice may, however, result in warping the platens of the press.

DRYING AND CONDITIONING GLUED JOINTS

So much moisture is added to the wood adjacent to the glue line by the large amount of water contained in glue mixtures that it must be taken care of. Table 2 shows the calculated percentages of moisture added to wood in gluing certain types of construction with different glue mixtures and spreads. The table is based on the assumption that the wood absorbs all of the water added by the glue. This is not strictly correct, since some of the glue squeezes out of the joints and some water evaporates during the pressure period. The calculated percentages, however, are reasonably close to the results obtained in actual gluing.

In order to obtain strong joints and to prevent warping, checking, sunken joints, and other defects in the finished article, it is essential that the wood after gluing be brought to the moisture content most suitable for the subsequent use of the article and that the moisture be evenly distributed throughout.

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[19] The hot-press process of plywood manufacture is not extensively used in the United States, but in European countries it is the prevailing method and is used not only with blood-albumin glues but often with casein glues as well.

TABLE 2.—*Percentages of moisture added to wood in gluing*[1]

Number of plies or laminations	Face	Crossband	Core	Total thickness unsanded	Percentage of moisture added by—		
					Glue mixed 1 to 2¼, if spread 60 square feet[2]	Glue mixed 1 to 2, if spread 50 square feet[2]	Glue mixed 1 to 1¾, if spread 30 square feet[2]
				Inches	*Per cent*	*Per cent*	*Per cent*
3	1/40-inch yellow birch		1/40-inch yellow birch	3/40	30.5	32.5	47.3
3	1/28-inch yellow birch		1/20-inch yellow birch	17/140	18.8	20.1	29.3
3	1/20-inch hard maple		1/20-inch hard maple	3/20	15.5	16.5	24.1
3	1/16-inch yellow birch		1/16-inch yellow birch	3/16	12.2	13.0	19.0
3	do		1/16-inch basswood	3/16	14.0	15.0	21.9
3	1/16-inch basswood		do	3/16	20.2	21.6	31.5
3	1/16-inch red gum		1/12-inch red gum	5/24	14.1	15.1	22.0
3	1/20-inch red gum		3/16-inch red gum	23/80	10.2	10.9	15.9
3	1/8-inch Douglas fir		1/8-inch Douglas fir	3/8	7.5	8.0	11.7
5	1/16-inch yellow birch	1/12-inch yellow birch	1/16-inch yellow birch	17/48	12.9	13.8	20.1
5	1/20-inch red oak	1/20-inch yellow poplar	3/16-inch yellow poplar	31/80	15.8	16.9	24.6
5	1/20-inch mahogany 1/20-inch red gum	do	5/8-inch chestnut	33/40	7.9	8.4	12.3
5	1/28-inch black walnut	1/20-inch red gum	15/16-inch red gum	621/560	5.3	5.6	8.2
5	1/8-inch white oak (quartered)	1/16-inch yellow birch	23/16-inch white pine	29/16	3.6	3.8	5.5
9	1/8-inch yellow birch	1/8-inch yellow birch	1/8-inch yellow birch	9/8	8.1	8.7	12.6
10	3/4-inch yellow birch	All plies or laminations parallel		7½	1.4	1.5	2.1

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[1] Percentages calculated from average weights (oven-dry based on volume when air-dry) of various species as given in Table 3 of Tech. Rpt. No. 84 of the National Advisory Committee for Aeronautics (*18*) or Table 2 of U. S. Dept. Agr. Bull. (*37*) 556. In the calculations it is assumed that all the surplus moisture added by the glue is absorbed by the wood.

[2] Single glue line per pound of dry glue.

CONDITIONING GLUED THICK STOCK

When the moisture increase in the wood due to a glued joint is small, such as in thick laminations (fig. 17, A, B, C, E, I, and J) dried to a suitable moisture content before gluing, only conditioning to a uniform moisture content is necessary.

Sunken joints are common defects in the manufacture of thick edge-glued lumber and are caused by surfacing the stock too soon after gluing. The wood right at the joint absorbs more water from the glue than the rest of the wood and therefore swells more. If the piece is surfaced before this excess moisture is distributed, more wood is removed along the joints than at intermediate points. Then, during subsequent drying and conditioning, greater shrinkage occurs at the joints than elsewhere, and permanent depressions are formed. Such depressions along the glue line may show very conspicuously in the finished panel when viewed under a side light. To avoid sunken joints in edge-glued lumber 1 inch thick it should be piled on stickers and dried for a period of two days in a kiln at 100° F., or five to seven days at 70° F.

DRYING PLYWOOD

It is necessary to dry a part of the moisture from plywood and veneer panels. (Fig. 3.) For example, assuming a moisture content of 3 per cent in the veneer and an increase of 14 per cent from the glue, the panels when removed from the clamps or press would contain about 17 per cent of moisture. Such percentages are common in many types of plywood immediately after gluing. For use in cabinets, in furniture, or in the interior of buildings more than one-half of this moisture should be removed before the panels are ready to be put into the finished article. For use outdoors or in unheated buildings, plywood containing about 12 per cent moisture will generally prove satisfactory. Where veneer is glued over a lumber core, the increase in moisture content of the whole panel at the time of removing the panels from the press is not so large as with thin plywood. However, in thick core panels the moisture from the glue is largely confined to the outside of the core and to the veneer. Therefore, the excess moisture of these parts is as great as in thin plywood and must be dried out or allowed to equalize through the core.

If the thick cores (1½ inches) are dried to a low moisture content before gluing, the water added in gluing the veneer onto the core may not bring the whole panel above 7 per cent moisture content. Under such a circumstance, the panels are sometimes stacked solid in large piles and allowed to condition. This requires a long conditioning period, and the absorption of moisture by the core after the crossbands have been glued to it subjects the whole panel to severe stresses.

A better and rapidly increasing practice for conditioning thick-core panels which contain excessive moisture is to place the panels on stickers and allow them to dry in panel kilns or in factory workrooms This practice allows the excess moisture to be dried from the panel faces where it is largely concentrated; and does not necessitate drying the thick-core stock to an extremely low moisture content before gluing. Panel kilns permit more rapid drying than in factory workrooms, give a better means for controlling the conditions during drying, and save factory space.

In panel kilns it is very easy to dry satisfactorily 3-ply and 5-ply panels in 24 hours. Results of tests at the Forest Products Laboratory in panel kilns show that under normal conditions the moisture added in gluing 3-ply panels, three-sixteenths of an inch thick, can be dried out satisfactorily in from 8 to 16 hours (*7*). These tests also indicate that the desired essentials in drying can be met by maintaining a constant temperature and relative humidity throughout the drying. To save time in such kiln operations it is advantageous to maintain conditions which correspond to a moisture content slightly below that to which the panels are to be dried.

Table 3 shows several combinations of temperatures and relative humidities, which will bring the stock to approximately the desired moisture content but which will not allow an appreciable amount of drying beyond this point.

TABLE 3.—*Combinations of temperatures and relative humidities suitable for drying plywood panels to moisture-content values of 6 to 12 per cent, inclusive*

Moisture content desired, per cent	Relative humidity for use with stated temperature [1]						
	70° F.	80° F.	90° F.	100° F.	110° F.	120° F.	140° F.
6	19	19	20	21	22	24	26
7	24	26	27	28	29	31	34
8	30	31	32	33	35	37	41
10	43	44	45	46	48	50	53
12	55	56	57	58	59	61	65

[1] The relative humidities shown for the lower temperatures and moisture-content values are obtainable ordinarily only during the winter season. Where a low moisture content is necessary during warm, humid weather, it can be obtained by raising the temperature.

Drying panels to an excessively low moisture content materially increases warping, checking, opening of joints, and other defects. Tests show that the amount of warping on 3-ply veneer panels is approximately proportional to the percentage of moisture removed from the panel in drying (*7*).

In a few instances plywood has been dried on mechanical veneer driers and on hot-plate presses. These methods, however, have been confined to plywood of a high moisture content, which was glued with water-resistant glue. Plywood dried in this way is usually comparatively thin and not of the highest quality. The high temperatures and pressures used in these methods have a molding effect on the wood and to some extent thus prevent face checking and warping.[20] Mechanical driers and hot-plate presses result in a quick drying process, but involve the use of more expensive equipment than is used in the other methods.

CONTROL OF GLUING CONDITIONS

A strong joint is characterized by complete contact of glue and wood surfaces over the joint area; a continuous film of good glue

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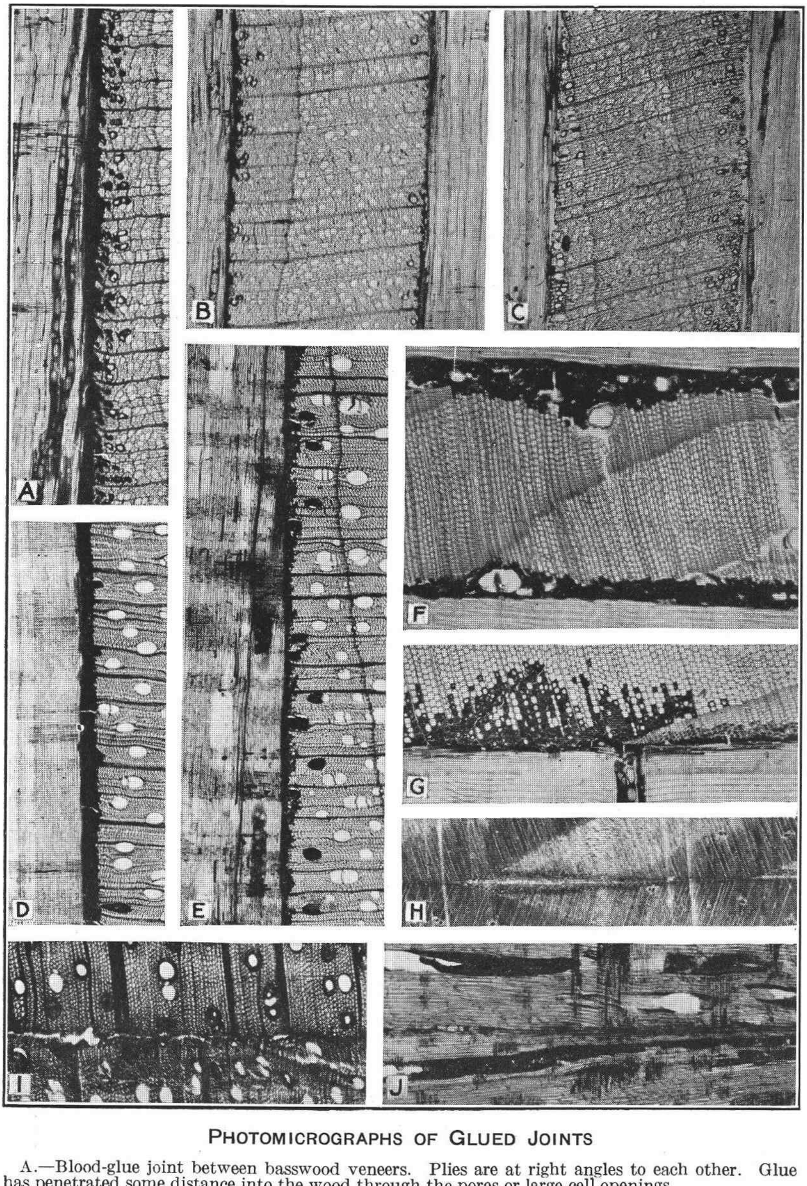
[20] HOOD, A. N., NIGHTINGALE, J. T., LELAND, F. R., and DIKE, T. W. MAKING PLYWOOD. (U. S. PATENT NO. 1,369,743.) U. S. Patent Office, Off. Gaz. 283 : 703. 1921.



PHOTOMICROGRAPHS OF GLUED JOINTS

A.—Blood-glue joint between basswood veneers. Plies are at right angles to each other. Glue has penetrated some distance into the wood through the pores or large cell openings.

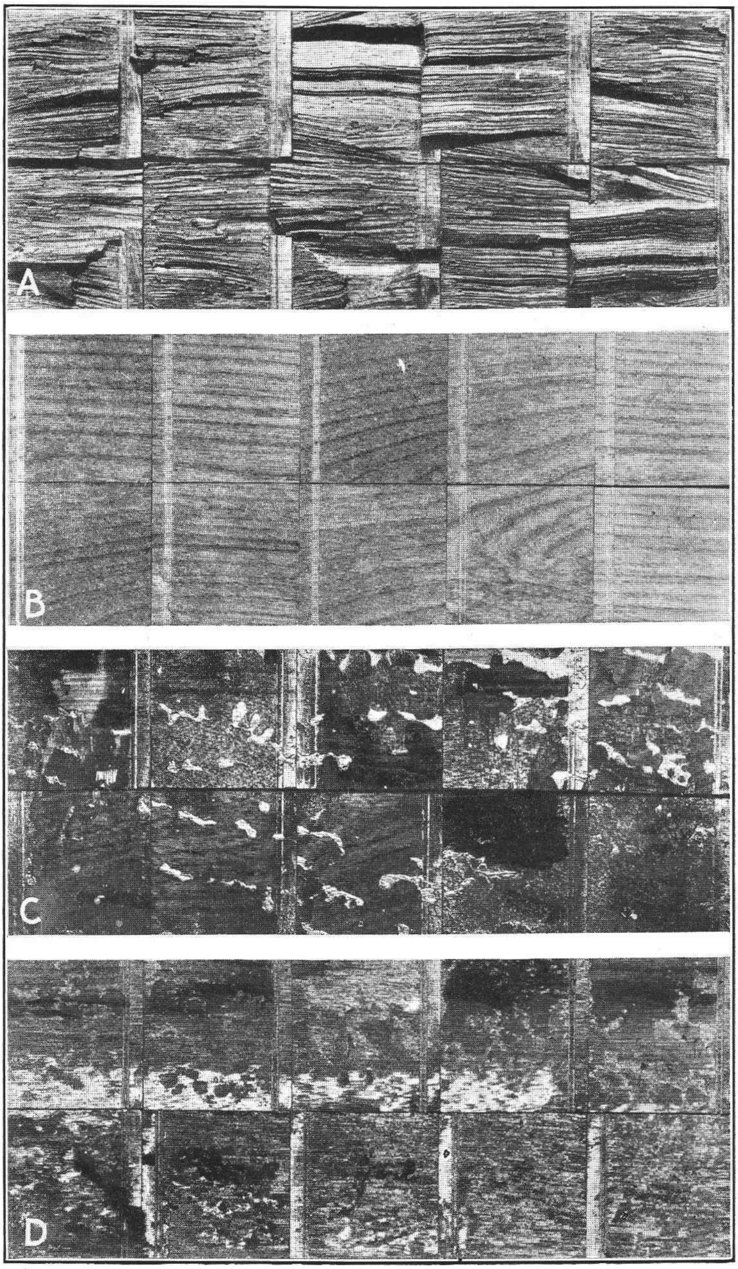
B and C.—Basswood plywood glued with animal glue under different gluing conditions. In B a slightly chilled glue and moderate pressure produced a strong joint. In C a thin glue and high pressure produced a typical starved joint.

D and E.—Birch plywood glued with blood glue at 50 and 200 pounds pressure per square inch, respectively. In spite of differences in penetration and glue-line thickness, the joints gave practically the same strength when tested.

F and G.—Blood glue between white pine veneer. In F only sufficient pressure was used to keep the veneers in contact. The wide glue lines contained numerous air pockets. In G 200 pounds pressure per square inch was used. Note thin glue line and variation in penetration between spring wood and summer wood.

H.—Douglas fir blocks glued with casein glue. Very little penetration, a thin glue line, and weak joints between summer wood portions as compared with spring wood. Dark areas along glue lines in spring wood were produced by staining from the glue.

I and J.—Cross and longitudinal sections of a starved joint in hard maple glued with animal glue. Note the hollow cylinders of glue in a part of the wood cells, caused by the glue tendrils shrinking.



TYPES OF JOINTS MADE WITH ANIMAL GLUE UNDER DIFFERENT GLUING CONDITIONS

A.—Well-glued joint; made with a proper relation between pressure and consistency of glue.

B.—Starved joint; resulted from the application of pressure while the glue was too thin. Occurs frequently on certain woods with animal and other thin glues.

C.—Chilled joint; glue formed into a firm jelly and the pressure applied was insufficient to bring complete contact. Light spots are areas of no contact.

D.—Dried joint; glue dried on the wood before pressure was applied. Poor adhesion throughout.

between the wood layers which is unbroken by air bubbles (pl. 9, F) or by foreign particles, and sufficient penetration of glue into the cell cavities to give adequate surface for adhesion. The thickness of glue film may vary considerably without appreciably affecting the strength of wood joints (pl. 9, D and E), provided the film is continuous.[21] Glue may stick wood layers together without penetrating the cell cavities [22] in the same way that glass and other nonporous substances may be glued. Microscopical studies of glue joints in wood, however, show that glue penetrates the cell cavities and other openings. Numerous shallow openings such as are made by penetration into the fiber cavities immediately adjacent to the glue line in plate 9, D, are better than penetration into a few deep but isolated large cells (*21*).

When glue is brought into contact with wood surfaces it does not pass through the cell walls but tends to enter the exposed cell cavities. Wherever the grain runs into the wood from the surface, as it nearly always does to a slight extent, the glue may penetrate for some distance along the cell cavities. (Pl. 9, A.) As the glue tendrils in the larger cell cavities dry and shrink they commonly take the form of long, hollow cylinders, leaving a film of glue clinging to the walls of the wood cells. (Pl. 9, I and J.) Deep penetration, which results in long tendrils of glue in the cell cavities, is not only unnecessary but may be harmful. When the wood has a dense cellular structure and the glue is thick, little or no penetration occurs, but the resulting bond is still adequate for some woods. Where no appreciable penetration occurs, the adhesion of glue to the wood substances is confined chiefly to the surface area of the wood and does not always give a bond equal in strength to that of the wood. If glue is relatively thin it may be pressed out from between the wood layers or else forced to penetrate into the open cells, giving what is commonly termed a "starved joint." (Pl. 9, C, I, and J.) In such cases the film of glue is not visible under the microscope and does not make a satisfactory bond. Therefore, moderate penetration along the glue line is preferable.

CORRELATION OF PRESSURE AND GLUE CONSISTENCY

Making strong glue joints depends primarily upon having the proper correlation of gluing pressure and glue consistency at the moment the pressure is applied. Long study and experiment at the Forest Products Laboratory have resulted in the recommendations shown graphically in Figure 6. If the glue is thin at the time of pressing a light pressure should be used, and if the glue is thick a heavy pressure should be used. By controlling the glue consistency

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[21] The relation between film thickness and adhesive strength reported by McBain and Lee (*35*) in polished metal surfaces joined with gums, resins, and waxes; namely, that "the thinner the layer of adhesive the stronger the joint," does not have a practical bearing upon wood joints. Many thousands of tests on wood joints made at the Forest Products Laboratory failed to disclose any direct relation between glue film thickness and joint strength.

[22] The relative importance of specific adhesion between glue and wood substance and of a purely mechanical bond in wood joints is a point upon which there is not complete agreement. McBain and Hopkins (*33*) have described a wood joint as "purely mechanical" in nature and state that specific adhesion is apparently lacking. This conception was later modified somewhat (*36*), but the character of adhesion is still described as chiefly mechanical. There is considerable evidence, however, that specific adhesion plays an important part in wood-glue joints (*3*, *13*).

the use of either extremely high or extremely low pressures may be avoided. Pressures from 100 to 200 pounds per square inch are recomended, although satisfactory results may be obtained over the entire range of pressures shown in Figure 6, provided the wood is strong enough to withstand crushing at the higher pressures. In using pressing equipment where the exact amount of pressure is not

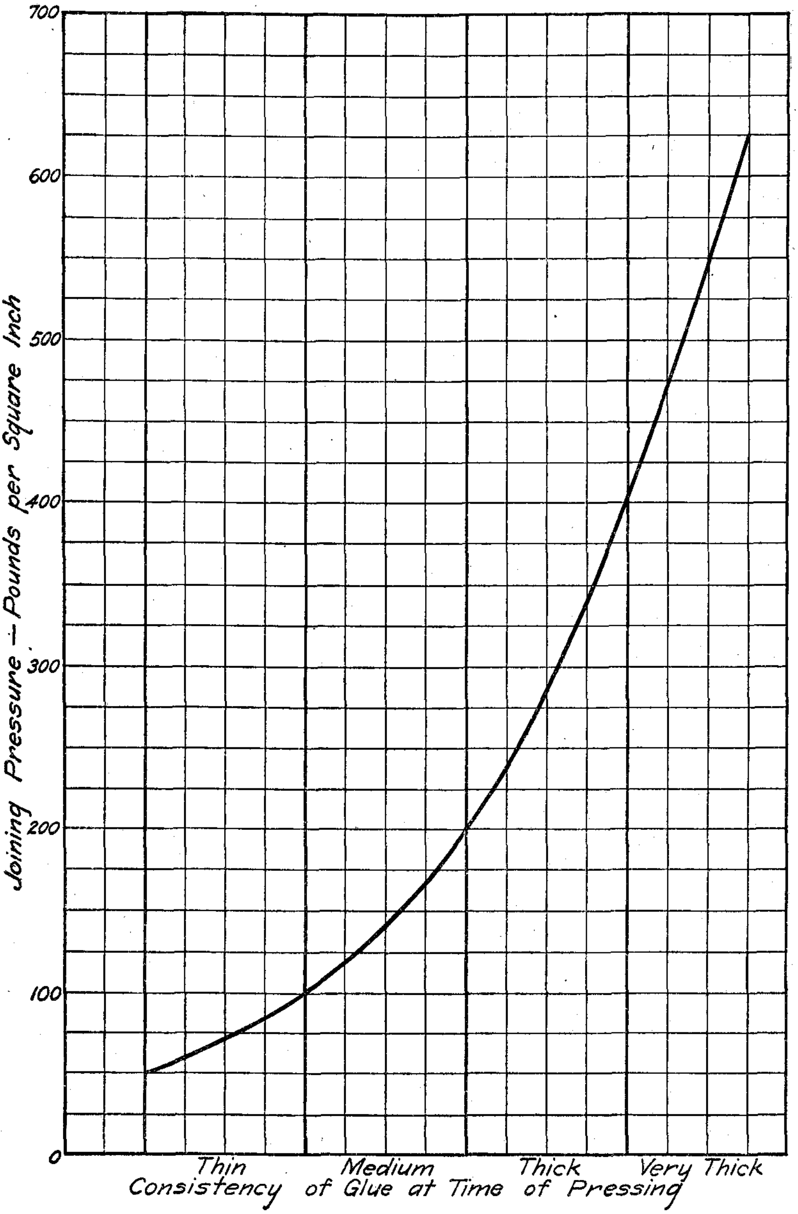

FIGURE 6.—Pressures recommended for glues of different consistencies at the time of pressing

known, the consistency of the glue used should be such that when a firm pressure is applied a small but definite amount of glue is squeezed out along the joint.

CONTROLLING GLUE CONSISTENCY

After glue has been spread on dry wood it thickens, some kinds more rapidly than others. Where coated laminations are laid together as soon as spread (closed assembly), the glue thickens much more slowly than where such laminations are left exposed for a time to the air (open assembly). If the closed-assembly method is used on unheated wood, an average spread of glue may be in good condition for 15 to 20 minutes. In the open-assembly method, glue quickly dries to the stage where proper adhesion is impossible. Where warm wood is used, dry spots in the glue line may occur within a very short time. Casein glues in particular dry and set very quickly on hot wood, and there is consequently the danger of poor joints from this cause. Casein, vegetable, or blood-albumin glues are at times unintentionally spread on wood which is still warm from the driers. Such practice is likely to cause "dried" joints (pl. 10, D) with all glues and "starved" joints (pl. 10, B) with animal glue.

Consistency of Animal Glue

With animal-glue solutions the consistency depends upon the cooling and the drying effects. For the first few minutes after an animal glue has been spread on the wood the cooling effect is much more important than the drying effect. Figure 7 shows the viscosity-temperature relationship for an animal glue mixed for use in woodworking. Near 140° F. a decrease of a few degrees makes but a slight change in the consistency of the glue solution, whereas a similar decrease in temperature in the region of 80° to 90° makes a marked change in consistency. In other words, an animal-glue solution as it approaches room temperature changes in viscosity very rapidly. This temperature-viscosity relationship, although general for animal glue, varies slightly with the grade and mixture of the glue solution. With other types of glues applied cold, a change of a few degrees in temperature without drying has relatively little effect.[23] High-grade animal glues and mixtures of low water content thicken to the proper pressing consistency quicker and at higher temperatures than low-grade glues of high water content. For this reason the grade and mixture of animal glue should be chosen to suit a particular gluing operation and to suit the temperature to be encountered.

Animal glues as ordinarily mixed for use are too thin for pressing immediately after being spread except for certain woods at low temperatures. In some gluing operations, therefore, animal glues should

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[23] The initial effect of heat in lowering the consistency of glue solutions is rather general with glues used in woodworking. Animal, certain jelly forms of blood-albumin, casein, and vegetable glues all become thinner with an increase in temperature. Prolonged heating, however, has a variable effect. With animal glue it results in a further decrease in viscosity, with blood glue a solidification occurs if the coagulating temperature or higher temperature is used, and with water-resistant casein glues the rate of any normal increase in the consistency is accelerated, and the working life of the glue is shortened (*12*).

be either allowed to thicken on the wood, or should be mixed thicker. Animal glue is at the best consistency for pressing just before it has formed a jelly. This consistency is obtained when the glue solution is thick enough to form short, thick strings when touched with the finger, but not thick enough to resist an imprint or a depression readily.

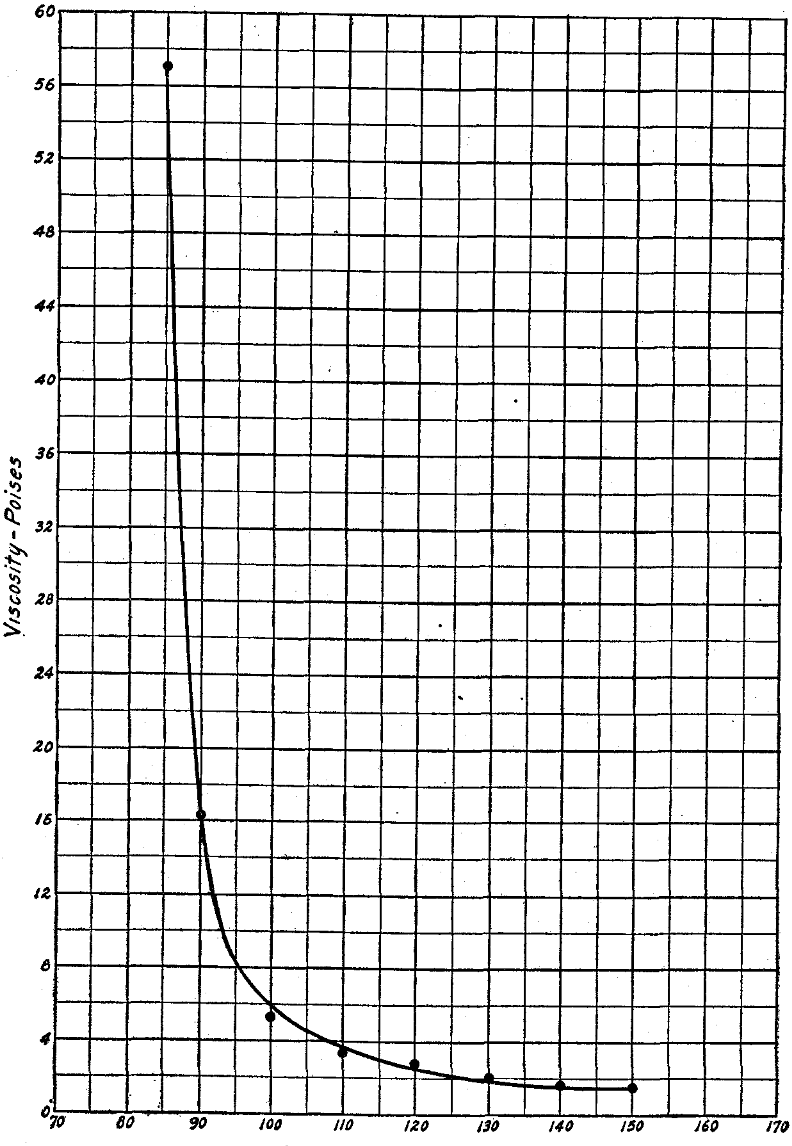

FIGURE 7.—Relation between temperature and viscosity of an animal-glue solution mixed for woodworking. The tests were made on an animal glue, equivalent to about a No. 12 in the National Association of Glue Manufacturers grades; mixed 1 part dry glue to 2¼ parts of water.

CONSISTENCY OF CASEIN, VEGETABLE, AND BLOOD-ALBUMIN GLUES

Most casein and vegetable glues are thick enough to press immediately after being spread, but if an unusually thin glue is used it should be allowed to thicken before pressing. Blood glues applied in jelly form are thick enough to press immediately, but when applied in liquid form they should be allowed to thicken slightly before being pressed. Blood glue may be spread on thin sheets of paper and dried. In this form it may then be inserted between wood layers and hot pressed.[24] Such blood glues retain moisture enough to allow the glue to unite the wood layers under the combined influence of the heat and pressure.

TYPES OF JOINTS RESULTING FROM DIFFERENT GLUING CONDITIONS

Plate 10 illustrates a well-made joint and three types of weak joints. The weak joints were produced as a result of not having a proper combination of glue consistency and pressure. The four sets of 10 specimens tested represent four joints, each glued under a different condition. In the first joint (pl. 10, A) failure occurred entirely in the wood because the joint was stronger in shear than the wood itself. In the other three joints of quite different appearance, failure occurred entirely in the glue line. Plate 10, B shows the "starved" type of joint, which is clean in appearance and shows no distinct film or layer of glue. The chilled type of joint (pl. 10, C) is due to the glue jellying (congealing without drying) and to the use of insufficient pressure to cause the glue to give complete contact. It occurs chiefly with animal glues. The "dried" joint (pl. 10, D) may occur with any glue that has lost so much water that it will not adhere to wood even under a very heavy pressure. In both the chilled and dried joints, contact occurs over only a part of the joint areas.

The relation of pressure and temperature to joint strength is illustrated in Figure 8, which shows the results of tests made on birch blocks glued with a good grade of animal glue at 70° and at 90° F. and at various pressures. The joints illustrated were coated with glue and placed together for 3, 12, and 25 minutes, respectively, before being pressed. The results of the three assembly periods, however, are averaged for each pressure used. At 70° the glue after being spread chilled in 1 to 2 minutes, and at the end of 3 minutes it formed a firm jelly. Such a firm jelly used with low pressures can not be relied upon for obtaining the best results. The curve at 70° shows a constant increase in average joint strength with increase of gluing pressures up to 400 pounds pressure.

The test results are very different, however, with the room and wood at 90° F. At this temperature the glue after being spread changed slowly in consistency, and at the end of 25 minutes it had not formed a firm jelly. The high pressures used at 90° F. squeezed out too much of the glue on the 3-minute assembly period, and therefore gave low average results. Good average results, however, were obtained at 50 and 100 pounds pressure per square inch,

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[24] A similar process is covered by the following: MCCLAIN, J. R. WOOD VENEER. (U. S. PATENT NO. 1,299,747.) U. S. Patent Office, Off. Gaz. 261; 286, illus. 1919.

but the minimum values were low. The most dependable results were obtained at 150 pounds pressure, where both the average and the minimum values were high. More uniform strength values could be obtained throughout the range of pressures and temperatures employed by the use of the correct assembly time for each temperature and pressure.

With the casein and the vegetable glues the consistencies are normally between those represented by thinly mixed warm animal glues and those represented by firmly jellied animal glues. The pressures that give the best joints with these glues are intermediate between those shown as optimum on the two curves of Figure 8. This is illustrated by the pressure-joint strength curve of Figure 9, which is based on joint-strength tests of 19 different hardwoods glued with a relatively thick casein glue. Here again the results for 1, 5, 12, and 25 minutes, closed assembly periods, are averaged. The best results, as indicated by the average joint-strength values and the average percentages of wood failure, were obtained with pressures of 200 and 400 pounds per square inch. The slight inferiority of the 100 pounds pressure would possibly disappear with a thinner mixture of glue and more easily glued woods.

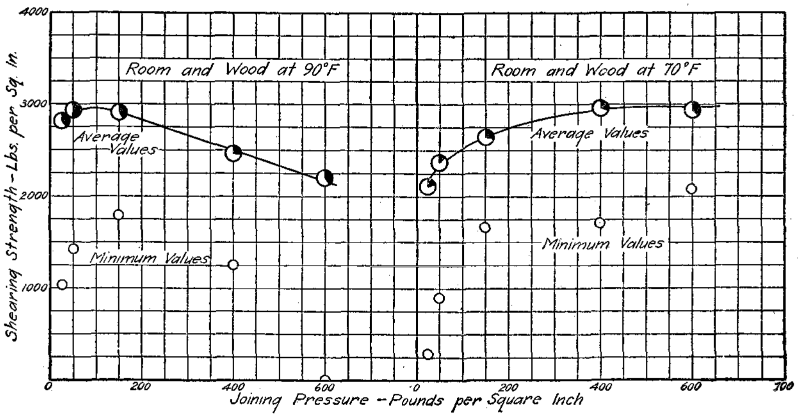


FIGURE 8.—Relation of gluing pressure to joint strength. The tests were made on yellow birch blocks glued with an animal glue. The shaded portion of the average points indicates the percentage of wood failure developed in testing the joints. Each average value shown represents at least 32 specimens

ASSEMBLY TIME

The time which elapses between the spreading of the glue on the wood and the application of pressure is called the "assembly time." In gluing plywood and veneered panels the common practice is to build up a stack of panels 2 feet or more in height and to place them under pressure at one time. (Pls. 5, 6, and 8.) In this method of assembly, 20 minutes or more may elapse from the time the first panel of a stack is spread with glue before it is under pressure, whereas the last panel spread with glue may be pressed within 2 minutes. In gluing thick pieces of wood the assembly time is usually short and in edge gluing it is generally less than 1 minute. The assembly times are largely influenced by the kind of apparatus used in the woodworking plant or by the production requirements and often can not be altered without considerable inconvenience and expense.

In the case of animal glue the effect of assembly time is closely related to the temperature of the room and the wood. Low temperatures of the room and the wood are best with short assembly periods and high temperatures of the room and the wood are best with long assembly periods. This is illustrated graphically in Figure 10. The data used are averages for joints of 12 hardwood species of high density. The ½-minute and 1-minute assemblies with the room and wood at 70° F., the 3 and 5 at 80°, the 8, 12, 18, and 25 at 90°, and the 12, 18, and 25 with the room at 90° and the preheated wood at 120° all gave joints of high quality although the joints on the preheated wood are not quite the equal of the others. The short-assembly periods at the high temperatures gave inferior joints. Long assemblies at the low temperature would have also produced unsatisfactory joints with the pressures used.

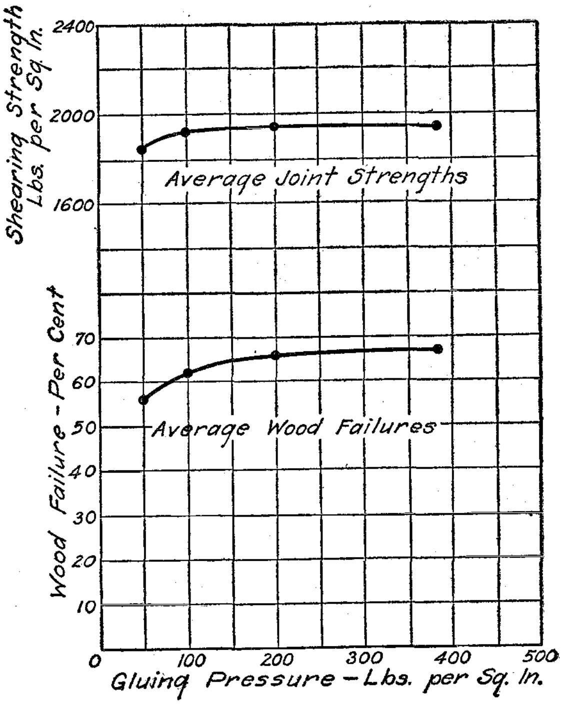


FIGURE 9.—Effect of gluing pressure on the joint strength of hardwoods glued with casein glue. Based on 19 hardwood species. Each average value shown represents at least 756 specimens

The assembly time for the casein and the vegetable glues has less effect on the strength of the joints than for the animal glue, either in blocks (parallel-grain construction) or in plywood. The consistency of the casein and the vegetable glues changes more slowly; therefore, moderate pressures (100 to 200 pounds per square inch) give satisfactory joints under assembly periods such as from one-half to 20 minutes. However, maximum joint strengths are normally not obtained in less than 5 to 7 minutes. For the casein glue, an assembly period of from 20 to 25 minutes is frequently not as good as an intermediate assembly period such as from 5 to 15 minutes.

If the assembly period must be long, it is best to use a thin glue heavily spread upon wood which is not excessively dry. For short assemblies thick glue spread thin on very dry wood is recommended. If the other controlled factors do not bring the glue to the preferred consistency in the time available, a pressure must be used to suit the consistency of the glue.

TEMPERATURE OF WOOD BEFORE GLUING

Because of the relation of temperature to the consistency of animal-glue solutions (fig. 7) and its effect upon the strength of joints (figs. 8 and 10) made with animal glue, preheating the wood before gluing is often inadvisable. Where the assembly time is long, the wood cold, and the glue of high grade, a moderate warming of the wood may be necessary to prevent the glue from thickening excessively before pressure is applied. On the other hand, where the assembly time is short, as in most edge-joint operations (pl. 7, B),

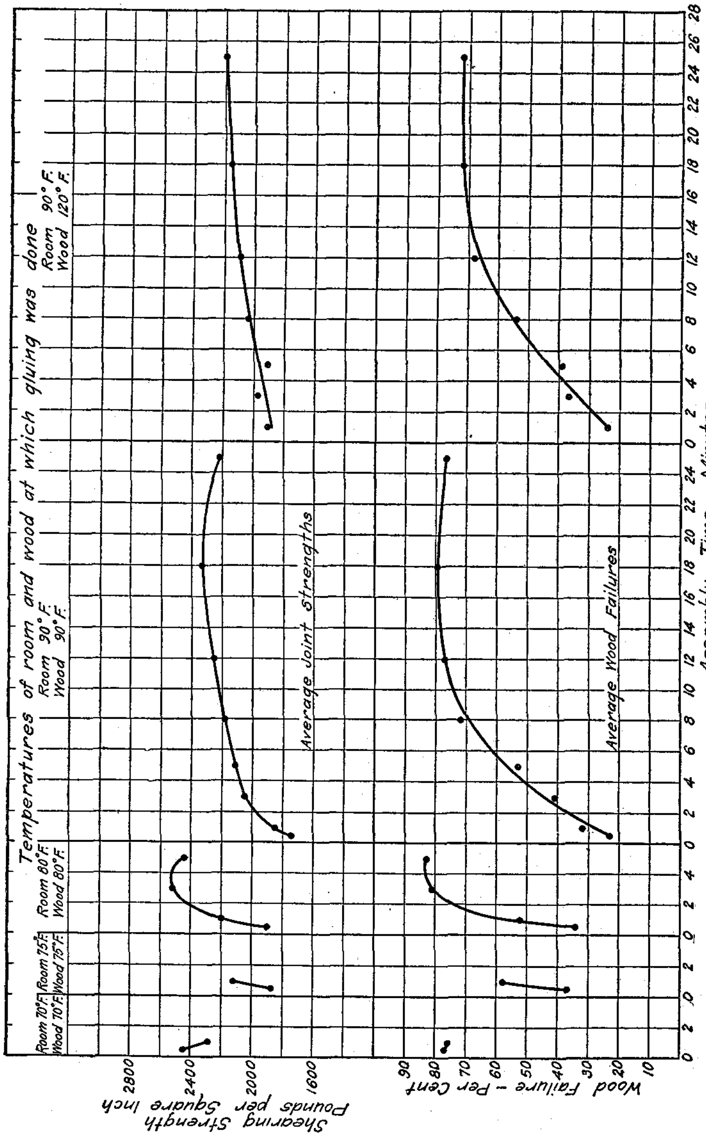
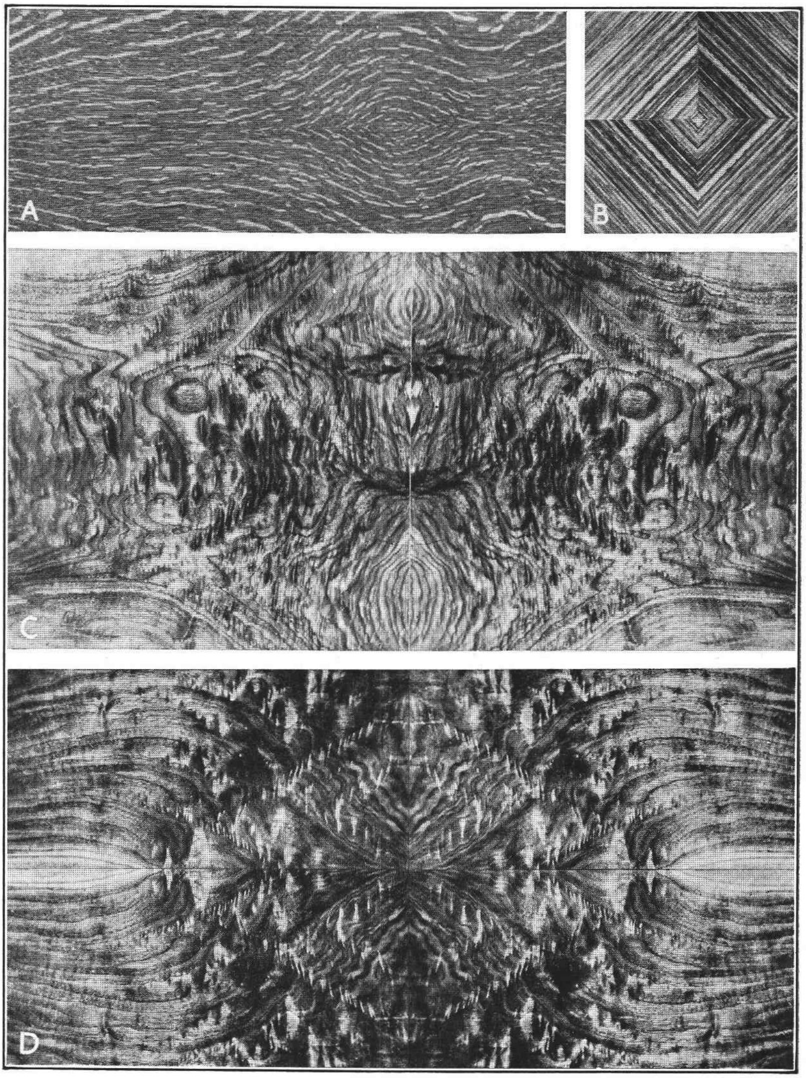


FIGURE 10.—Relation of assembly time and temperature to the joint strength of animal glue. Based on 12 hardwood species; gluing pressures 100 to 200 pounds per square inch. Each average value represents at least 75 specimens



PLYWOOD FACES MATCHED FROM FIGURED VENEER

A.—A sawed quartered-oak veneer face matched by turning over one piece from the side.

B.—Striped effect produced from edge-grained veneer. Two of the four pieces shown have been turned over in matching.

C.—Stump veneer matched by turning one piece over endwise.

D.—Symmetrical effect obtained by turning over two of four adjacent pieces of veneer.

preheating the wood usually results in weak joints, especially if the glue is of low grade. In commercial practice starved joints (pl. 10, B) resulting from overheating are more common than chilled joints (pl. 10, C) resulting from a lack of heating. Practically all types of commercial gluing can be satisfactorily and conveniently done if the temperature of the wood is within the range of 70° to 90° F. (See Tables 7 and 8 for recommended gluing schedules.)

THE QUANTITY OF GLUE SPREAD

An excessive glue spread wastes glue, adds more water to the wood than necessary, and may cause the wood to slip out of position while being pressed. The general relation of quantity of glue spread to joint strength is illustrated in Figure 11, which is based upon laboratory tests upon plywood glued with vegetable glue. With casein and vegetable glues, spreads of 65 pounds of wet glue per 1,000 square feet of surface give high strength values when the other gluing conditions are favorable. This is equivalent to a glue spread of 45 square feet of single glue line per pound of dry glue, where a mixture of 2 parts of water to 1 part by weight of glue is used, or it is equivalent to 48 square feet for a mixture of 2⅛ parts of water to 1 part by weight of glue. For the best results under a wide range of conditions, a glue spread of 75 pounds per 1,000 square feet is recommended. This is equivalent to 37 square feet per pound of dry glue mixed 2 to 1, or 40 square feet per pound of dry glue mixed 2⅛ to 1. Thicker spreads than 80 pounds of wet glue per 1,000 square feet are unnecessary under ordinary gluing conditions. If the strength requirements of the glued product are not very high,

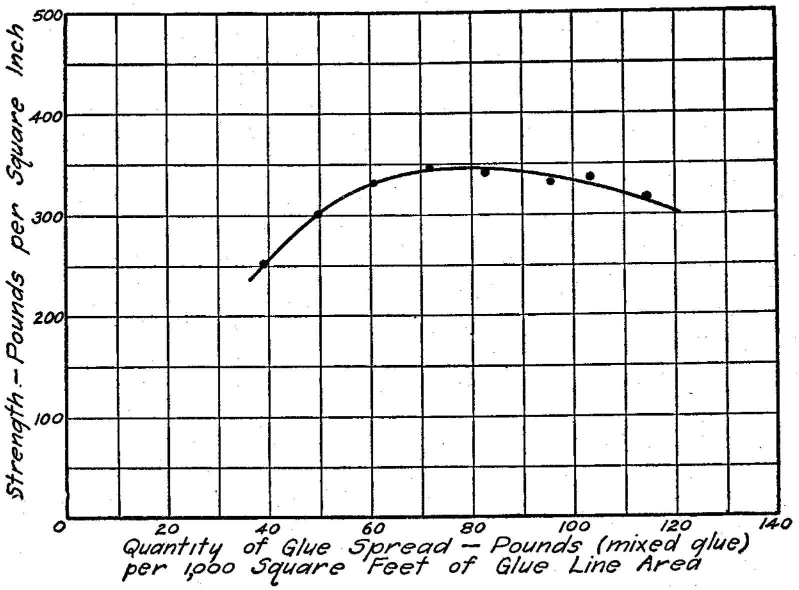


FIGURE 11.—Effect of quantity of glue spread on joint strength of vegetable glue. Tests were made on three-ply cross-banded panels with all plies of $\frac{1}{16}$-inch birch. Values are averages of 25 to 230 specimens

glue spreads as thin as 60 to 80 square feet of glue line per pound of dry glue may be used if other gluing factors are properly controlled. Differences of as much as 50 per cent in the area covered per pound of dry glue may be required between a thick or thin glue when used on rough, smooth, porous, or nonporous wood surfaces.

GLUING END-GRAIN WOOD

The recommendations thus far presented relate chiefly to the gluing of side-grain surfaces. Such joints can be made as strong as the wood itself. End-grain to end-grain joints, however (fig. 2, A), are much more difficult to glue and can not be glued strong enough to break the wood.

For gluing end-grain surfaces with animal or casein glue both surfaces should be sized with a mixture of 1 part of glue to 3 to 5 parts of water, depending on the grade of glue, and the sizing coat should be allowed to dry. Both surfaces should then be coated with a thick glue mixture (about 10 per cent less water than is used in side-grain gluing for any specified grade, and pressed at 200 pounds per square inch.

LAYING FIGURED VENEER

Highly figured burl, stump, and crotch veneers (pl. 2, A, and pl. 11, C and D) generally necessitate the gluing of end-grain surfaces. It is considered good practice in gluing these veneers to size both sides of the veneer with warm animal glue mixed 1 part of glue with 3 to 5 parts of water, depending upon the grade of glue, and allow the sizing coat to dry.[25] After the sizing has thoroughly air-dried, the veneer sheets should be redried between heated wooden cauls. While the face veneer is being sized and dried, the crossband veneer should be laid onto the core and then dried and surfaced. The dry cross-banded core should be spread next with a thick glue. Animal glue may be used on the crossband if allowed to chill somewhat before the face veneer is brought into contact because the warm cauls will soften the glue sufficiently to permit adhesion. Finally, the face veneer should be laid in place and pressed as quickly as possible.

GLUING CHARACTERISTICS OF DIFFERENT WOODS

While practically all species of wood commonly used in the United States can be glued successfully, some require more care in gluing than others in order to insure joints of the highest strength.

Extensive gluing tests have been made at the Forest Products Laboratory on 40 common species, in which vegetable glue, casein glue, and animal glue were used.[26] The wood, in pieces three-fourths of an inch thick, 5 inches wide, and 12 inches long, was glued into 1½ by 5 by 12 inch blocks, then cut into specimens and tested as described in the Appendix, page 69. The gluing was done under conditions which cover the general range found in commercial prac-

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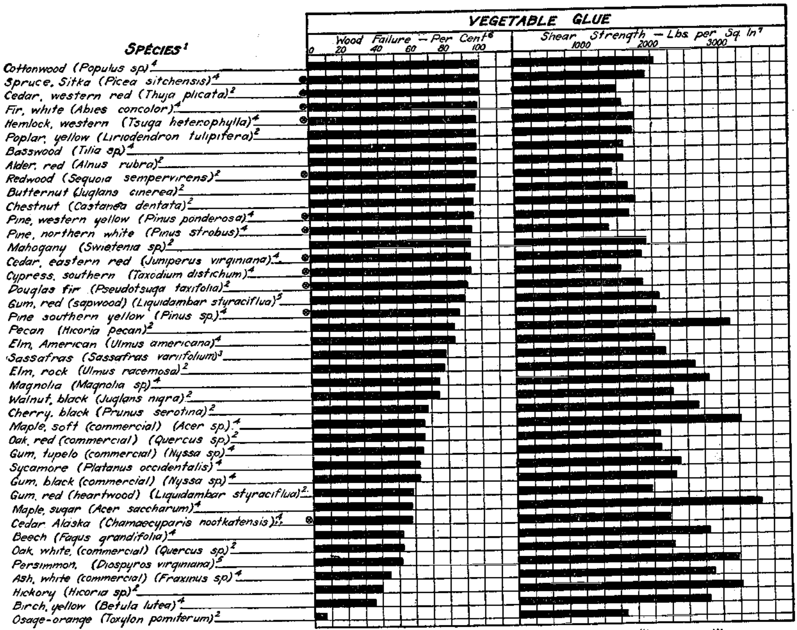
[25] Various secret sizing formulas are used in the woodworking trade, which, in addition to glue, usually contain other materials.

[26] Blood-albumen glues, owing to their small use in this country, were not included in these tests, and liquid glues, owing to the wide range in grades, were also omitted.

tice. The test data obtained were analyzed, and the combinations of conditions which had given the most satisfactory results for each glue on all species were selected. With the exception of the Osage-orange species, the combinations selected for the casein and for the vegetable glues were applied alike to all species. The data for animal glue were selected to give a fair comparison of the remaining 39 species. The average test results are shown in Figures 12, 13, and 14.



1-Common and scientific names are the standard names given in U.S. Dept Agr Misc Circ 92 except those designated "(commercial)"
2-Heartwood
3-Mostly heartwood
4-Heartwood and sapwood mixed or not identified
5-Sapwood
6-Wood failure per cent indicates the estimated proportion of the joint area of the specimen where wood fibers were torn away in testing
7-The shear strength of joints is not comparable with the shear strength of solid wood published in US Dept Agr Bull 556 and elsewhere, due to differences in the test methods and specimens used
⊗ Indicates woods of the softwood or non-porous class, others belong to the hardwood or porous class

FIGURE 12.—Results of tests on joints of various woods glued with vegetable glue. Values shown are averages of 45 to 180 specimens

The test results are expressed both in percentage of the joint area in which failure occurred in the wood and in the breaking strength in pounds per square inch of joint area.[27] Failure in joints usually occurred partly in the wood and partly in the glue line. "Percentage of wood failure" refers to the proportion of the joint area of the specimens where wood fibers were torn away in testing. In Figures 12, 13, and 14 the species are arranged in order of wood failure developed in the tests.[28] Wood failure combined with the shear strength of the joint is used as the criterion for judging the effectiveness of the gluing. Where the wood failure is at or near 100 per cent the joints obviously had been glued satisfactorily, irrespective of the

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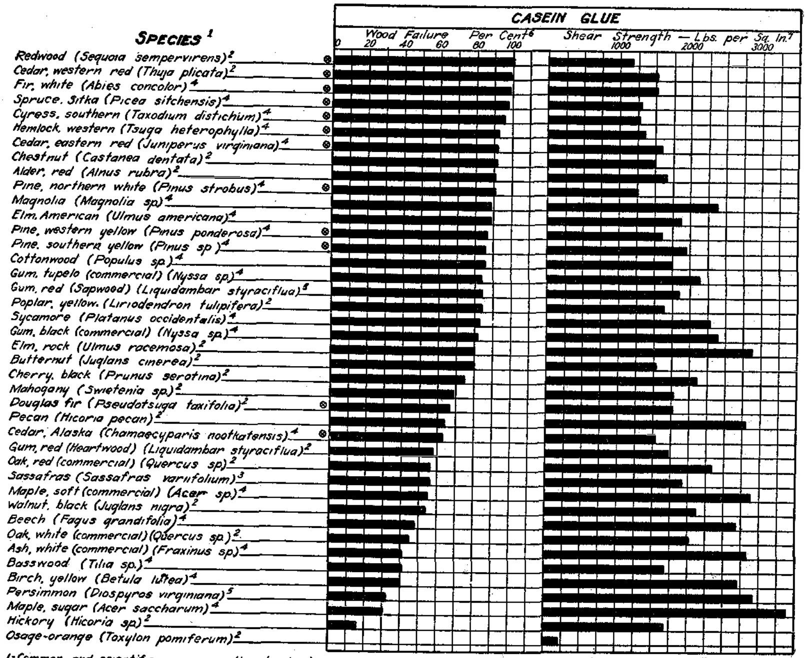
[27] On account of difference in testing apparatus and character of test specimen the strength values given in this bulletin for joints are not comparable with the strength data published elsewhere on solid wood.

[28] Where two or more species showed the same average percentage of wood failure they are arranged in descending order of the strength of the joints.

joint strengths obtained. In many species the percentages of wood failure is considerably less than 100 per cent, and in such cases the joint strengths must also be considered in determining the success obtained. The strength of the joints in most species is equal to or greater than the calculated strength of the wood itself.

The relative positions of the different species with respect to wood failure developed in these tests vary with the different glues, but in general they are similar. Woods of low joint strength, such as Sitka spruce, western hemlock, and redwood, show a high percentage of wood failure, and woods of high joint strength, such as sugar maple persimmon, and white ash, show a low percentage of wood failure. For any one glue, the woods giving similar joint strengths vary considerably in the amount of wood failure, and those with lower percentages of wood failure, therefore, require more care in gluing to obtain the full strength of the wood.



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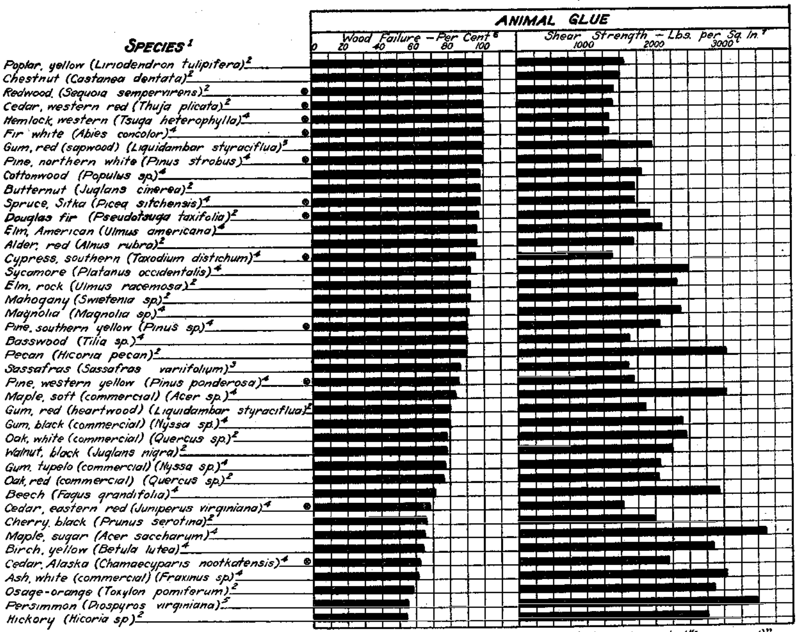
4-Heartwood and sapwood mixed or not identified
5-Sapwood
6-Wood failure per cent indicates the estimated proportion of the joint area of the specimen where wood fibers were torn away in testing.
7-The shear strength of joints is not comparable with the shear strength of solid wood, published in U.S. Dept. Agr. Bul. 556 and elsewhere, due to differences in the test methods and specimens used
⊗-Indicates woods of the softwood or nonporous class; others belong to the hardwood or porous class

FIGURE 13.—Results of tests on joints of various woods glued with casein glue. Values shown are averages of 60 to 240 specimens

RELATION OF DENSITY OF WOOD TO GLUING PROPERTIES

The density of wood has a rather close relation to its gluing properties. This is illustrated in Figure 15, in which the results of the tests described on page 42 and shown in Figures 12, 13, and 14 are averaged and plotted against the average specific gravity of the species tested. The wood failure and the shear strength of the glue joints tested have a distinct relation to the specific gravity of the wood glued. The conformity to this general rule is closer where the results obtained with the three glues are averaged than where they are taken individually. The variation from this rule for certain woods is due to other factors, which are discussed below. The increase in the shear strength with the specific gravity of the different species is similar to that for solid wood (*38*), and under good gluing conditions the joint strengths are not seriously affected by the percentage of wood failure developed in test. This indicates the impracticability of judging the strength of joints on the type of failure alone.[29]



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5-Sapwood
6-Wood failure per cent indicates the estimated proportion of the joint area of the specimen where wood fibers were torn away in testing.
7-The shear strength of joints is not comparable with the shear strength of solid wood, published in U.S. Dept. Agr. Bul. 556 and elsewhere due to differences in the test methods and specimens used.
● Indicates woods of the softwood or nonporous class; others belong to the hardwood or porous class.

FIGURE 14.—Results of tests on joints of various woods glued with animal glue under good gluing conditions. Values shown are averages of 30 to 180 specimens

Hardwoods (porous woods) as a class require more care in gluing than softwoods (nonporous woods). This difference is most apparent with thin glue, for example, a warm animal glue may penetrate excessively into the porous woods and thus give starved joints. Figure 16 shows the results of tests made with animal glue under starved-

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[29] In commercial work a rough measure of a good joint is whether or not it is stronger than the wood. If, when the joint is broken, the break occurs mostly in the wood the glue joint is considered entirely successful, but if the break is mostly in the glue the joint is not ordinarily considered entirely satisfactory, regardless of the force required to break it. With such a measure of quality much depends upon the strength of the wood, and there is consequently great danger of misjudging the real strength of the joint.

joint conditions but with the same grade of glue as used in Figure 14, where the joints were made under good conditions. In comparing Figure 16 with Figure 14 it may be observed that in the joints of most of the nonporous woods the shear strength and the percentage of wood failure remain almost the same for both the starved and good gluing conditions, however, in the joints of most of the porous woods the shear strength and the percentage wood failure differ greatly.

Sapwood is generally more porous and contains less gums, oils, resins, tannin, or other infiltrated material than heartwood. The results for many of the species given in Figures 12, 13, 14, and 16 were obtained on glued combinations of heartwood and sapwood. In Table 4 the results of special tests on heartwood and on sapwood are shown for nine species which were glued with animal, casein, and vegetable glue, respectively. The results for the heartwood and the sapwood of some species are as different as the results between some distinct species. Infiltrated materials in the woods used for these tests, especially in the red gum and in the black walnut, interfered with the glue adhesion. Tests made on the various woods which were not previously treated to curtail the interference on infiltrated materials on the glue adhesion gave varied results with different glues. For example, the heartwood of eastern red cedar glued satisfactorily when the casein and the vegetable glues were used, but glued unsatisfactorily when the animal glue was used. The free alkali of

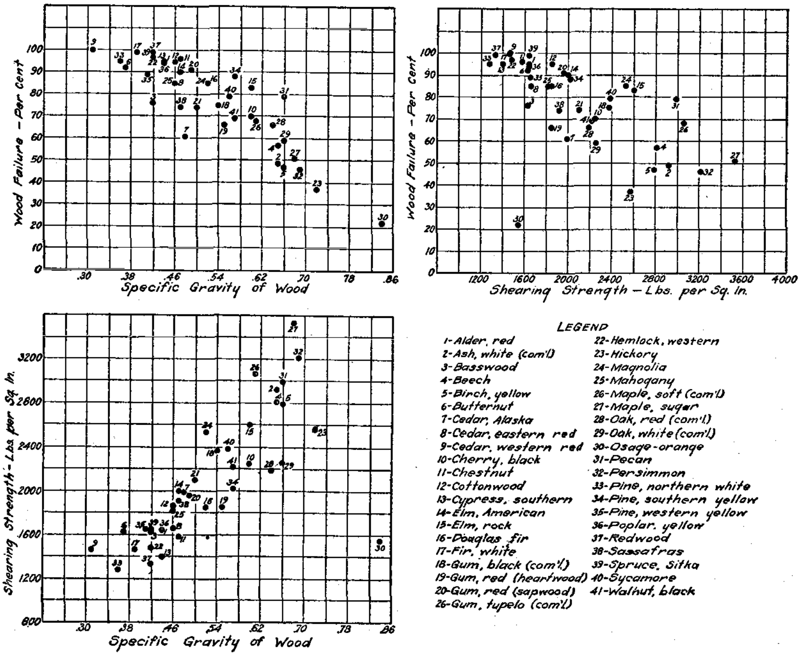


FIGURE 15.—Relation of density of wood to the shear strength and wood failure of glued joints. Averaged results with animal, casein, and vegetable glues given in Figures 12, 13, and 14

Table 4.—*Results of tests on gluing properties of heartwood and sapwood*[1]

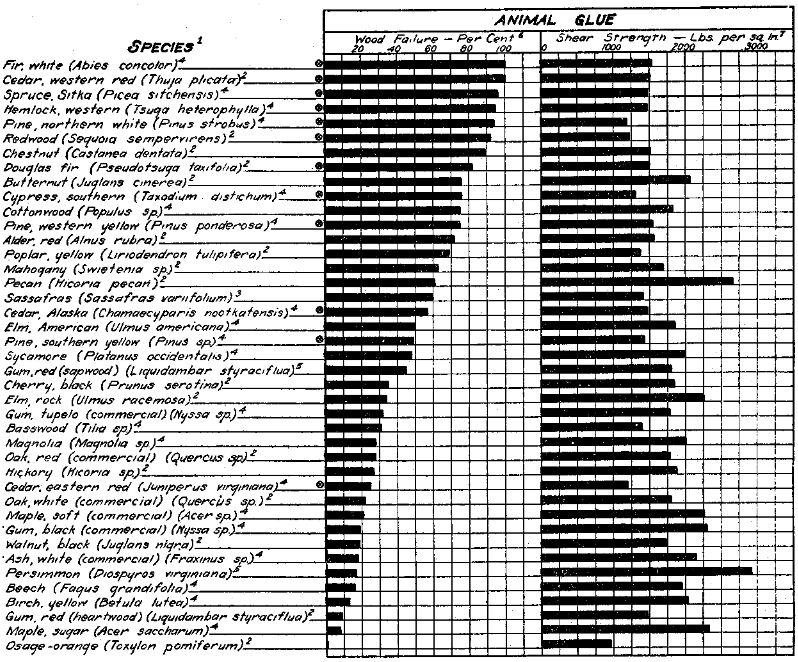
[H=heartwood; S=sapwood]

Species	Animal glue[2]			Casein glue			Vegetable glue		
	Shear strength	Wood failure	Specific gravity[3] of wood	Shear strength	Wood failure	Specific gravity[3] of wood	Shear strength	Wood failure	Specific gravity[3] of wood
	Lbs. per sq. in.	*Per cent*		*Lbs. per sq. in.*	*Per cent*		*Lbs. per sq. in.*	*Per cent*	
Ash, white .... H	2,354	89	0.54	2,114	59	0.55	2,320	58	0.53
Do .... S	2,259	94	.53	2,272	53	.53	2,332	70	.50
Birch, yellow .... H	2,711	73	.66	2,321	32	.65	2,711	36	.66
Do .... S	3,174	64	.64	2,957	49	.66	2,879	48	.66
Cedar, eastern red .... H	1,345	28	.47	1,686	85	.48	1,660	92	.48
Do .... S	1,919	96	.46	1,518	99	.39	2,052	95	.46
Gum, red .... H	1,975	81	.53	1,731	58	.54	1,975	59	.55
Do .... S	2,080	100	.51	1,849	84	.52	2,103	90	.46
Magnolia .... H	2,352	96	.47	2,279	78	.53	2,587	88	.51
Do .... S	2,573	92	.53	2,501	100	.48	3,066	62	.58
Maple, sugar .... H	3,998	66	.71	3,854	39	.71	3,874	50	.72
Do .... S	3,905	70	.68	3,028	26	.67	3,287	62	.66
Pine, northern white .... H	1,258	100	.36	1,202	85	.37	1,254	95	.38
Do .... S	1,476	100	.37	1,351	94	.37	1,449	97	.39
Pine, western yellow .... H	1,605	68	.39	1,590	80	.40	1,798	92	.44
Do .... S	1,531	100	.38	1,616	94	.37	1,538	99	.38
Walnut, black .... H	2,104	72	.56	2,124	54	.58	2,303	74	.53
Do .... S	2,738	85	.53	2,558	55	.57	2,672	88	.53

[1] Each test value shown represents 20 specimens or more.

[2] Used under good gluing conditions (see Tables 6 and 7).

[3] Specific gravity is based on oven-dry weight and volume at about 7 per cent moisture content.



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3-Mostly heartwood
4-Heartwood and sapwood mixed or not identified
5-Sapwood
6-Wood failure per cent indicates the estimated proportion of the joint area of the specimen where wood fibers were torn away in testing
7-The shear strength of joints is not comparable with the shear strength of solid wood, published in US Dept Agr. Bul. 556 and elsewhere, due to differences in the test methods and specimens used
⊗-Indicates woods of the softwood or nonporous class; others belong to the hardwood or porous class

Figure 16.—Results of tests on joints of various woods glued with animal glue under starved joint conditions

the casein and vegetable glues is thought to have counteracted the interference of the infiltrated materials in the wood with the glue adhesion. The heartwood of birch glued very satisfactorily when the animal glues were used but glued less satisfactorily when the casein and vegetable glues were used. In the tests described on page 42 the heartwood of Osage-orange glued satisfactorily with animal glue but unsatisfactorily with casein glue. (Figs. 13 and 14.)

TREATING THE WOOD BEFORE GLUING

In certain species treating the wood with a chemical before gluing improves the joint strength. Of several treating materials tested at the Forest Products Laboratory a 10 per cent solution of caustic soda generally proved to be the most effective.[30] In these tests the wood surfaces to be joined were brushed with the caustic soda solution; after about 10 minutes they were wiped with a cloth to remove any excess solution or dissolved material and allowed to dry before being glued. The same grade of glue was used, and the density of the wood tested was substantially the same. These tests show a decided improvement in the joint strength of the hard maple, yellow birch, white oak, red oak, red gum (both heartwood and sapwood), black cherry, and basswood over tests on untreated woods of the same species. Osage-orange treated with the caustic solution and then glued with a casein glue gave satisfactory joints. Furthermore, treating with caustic soda the surfaces to be joined prevents starved joints. This is indicated by the test data obtained from hard maple glued with an animal glue, which is given in Table 5.

Table 5.—*Results of caustic soda treatment on joints of hard maple glued with an animal glue*[1]

Condition of specimen	Shear strength of joint	Wood failure
	Lbs. per sq. in.	*Per ct.*
Wood untreated (starved joint conditions)	2,440	13
Wood treated with 10 per cent caustic solution (starved joint conditions)	3,564	82

[1] Each test value shown represents 50 specimens.

Although chemical treatments of the wood surfaces before gluing result in better joints with certain species that require great care in gluing, such treatments are time consuming and therefore add to the expense of gluing. Ordinarily, good glued joints can be secured by properly regulating the gluing practice (p. 32) so that the chemical treatment of the wood is unnecessary.

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[30] With hickory, black cherry, and red gum (heartwood) glued with casein glue, a treatment of milk of lime (10 parts of hydrated lime to 90 parts of water) gave slightly better results than were obtained with the caustic soda treatment.

GLUING PLYWOOD OF DIFFERENT SPECIES

The results shown in Figures 12 to 16 were obtained on joints made from lumber approximately three-quarters of an inch thick. Similar experiments on plywood joints were not made on all the species; however, a great deal of experimental plywood has been glued from some of the species, and it is believed that the same general principles, based on the inherent characteristics of the wood, hold for the plywood as for the lumber.

The results obtained in gluing smoothly planed lumber may vary somewhat from those obtained in gluing rotary-cut or sliced veneer. When glued into plywood and tested, badly checked veneer shows a higher percentage of wood failure and a lower joint strength than firm, smooth veneer (*8*). In a plywood test, therefore, the relative positions of the species in Figures 12 to 16 would probably vary somewhat.

TENDENCY OF WOODS TO BE STAINED BY GLUE

In gluing veneer into plywood the tendency of the different species to be stained by the glue is often a matter of importance. This applies particularly to the face veneer of plywood that is to receive a finish. The tendency of various woods to stain when glued with a strongly alkaline glue is indicated in Table 6. Most discoloration of the wood when glued is the result of a reaction between the free alkali of the glue and materials in the wood. The shade varies for different woods. For example, in oak the discoloration is brown; in mahogany, dark red; and in redwood, almost black. The different kinds of glues vary in their tendency to stain. (See Table 1.) Blood-albumin glues do not ordinarily contain much free alkali; nevertheless the dark-colored blood albumin may penetrate porous woods to such an extent as to discolor thin veneers. Animal and liquid glues do not normally produce any objectionable discoloration.

TABLE 6.—*Tendency of various woods to be stained by a strongly alkaline glue*

Species of wood [1]	Amount of staining			Species of wood [1]	Amount of staining		
	Marked	Slight	Very slight or none		Marked	Slight	Very slight or none
Ash			X	Mahogany	X		
Basswood		X		Maple	X		
Beech	X			Oak, red	X		
Birch	X			Oak, white	X		
Cedar, Spanish	X			Pine, southern yellow			X
Cherry, black	X			Pine, northern white		X	
Cottonwood			X	Pine, western yellow			X
Cypress, southern	X			Poplar, yellow			X
Douglas fir	X			Redwood	X		
Elm, American			X	Spruce, Sitka		X	
Gum, black		X		Sycamore		X	
Gum, red	X			Walnut, black	X		
Gum, tupelo		X					

[1] Heartwood was used in all species where it could be identified.

Staining may be reduced by drying the wood to a low moisture content before it is glued and then drying the glued stock as soon as possible after the glue is applied as described on pages 16 and 29. To further aid in the prevention of veneer surface discoloration a thick veneer and a thick glue mixture should be used. Surface stains may be removed by bleaching.[31]

GLUING RECOMMENDATIONS FOR DIFFERENT SPECIES AND GLUES

The results shown in Figures 12, 13, 14, and 16 indicate that many woods glue similarly under the same gluing conditions and that there is a gradual transation from those requiring the least to those requiring the most care in gluing. Consequently, there is no sharp line or division point by which the wood species can be separated into distinct classes or groups. It is also apparent that conditions which may give satisfactory joints on some species may be entirely unsatisfactory for others.

The gluing schedules, presented in Table 7, and their application to the 40 species of wood listed in Table 8, are intended as a guide to good gluing practice. Gluing schedules A1, A2, and A3 apply to animal glue; C1 and C2 to casein glue; and V1 and V2 to vegetable glue. The A1, C1, and V1 schedules are less exacting than the A2, C2, and V2, respectively, and the A2 schedule is less restricted, in turn, than the A3. Species for which one of the less exacting schedules is recommended may also be glued under a more restricted schedule. For example, if ash, both heartwood and sapwood (Table 8), is glued with animal glue, the gluing schedule A3 should be used. Any of the four sets of conditions listed under A3 (Table 7) may be used successfully. Ash can not be glued under less exacting Schedules A2 or A1 without some sacrifice in joint strength. Likewise, with casein and vegetables glues the more restricted Schedules C2 and V2 are recommended for ash. Yellow poplar is glued more easily than ash, and Schedules A2, C1, and V1 are recommended, respectively, for animal, casein, and vegetable glues. Any of the gluing conditions listed for yellow poplar as well as those given under the most restricted schedules of A3, C2, and V2 may be safely used. Gluing Schedule A1 is not recommended for yellow poplar. In a few cases, for example, in the Schedules A3, C2, and V2 listed for the heartwood of beech, the most restricted conditions do not give entirely satisfactory results, and an improvement in the gluing of such woods is possible by treating it previous to gluing (p. 48).

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[31] Sponging the stained surface with an oxalic-acid solution, prepared by dissolving 1 ounce of oxalic-acid crystals in about 12 ounces of water, will ordinarily remove glue discoloration. A more effective way is to moisten the wood first with a sodium-sulphite solution (1 ounce sodium sulphite to 12 ounces water) followed by the application of oxalic acid. The acid must be thoroughly removed from the wood afterwards or it may affect the finish. The oxalic acid is poisonous and should be handled with care.

TABLE 7.—*Gluing schedules*

Class or gluing schedule	Glue-water proportion [1] by weight	Glue spread	Temperature of the wood	Pressure	Closed [2] assembly time
		Lbs. per 1,000 sq. ft. [3]	*°F.*	*Lbs. per sq. in.*	*Minutes*
A1[4]	1 to 2¼	60 to 65	70	100 to 150	0 to 1
	1 to 2¼	65 to 70	80	100 to 150	1 to 5
	1 to 2¼	70 to 75	90	100 to 150	3 to 20
	1 to 3	70 to 75	90	100 to 150	5 to 20
A2[4]	1 to 2¼	65 to 70	70	125 to 175	½ to 1
	1 to 2¼	70 to 75	80	125 to 175	2 to 5
	1 to 2¼	75 to 80	90	125 to 175	7 to 18
	1 to 2¾	75 to 80	90	125 to 175	10 to 20
A3[4]	1 to 2¼	65 to 70	70	150 to 200	½ to 1
	1 to 2¼	70 to 75	80	150 to 200	3 to 5
	1 to 2¼	75 to 80	90	150 to 200	10 to 18
	1 to 2½	75 to 80	90	150 to 200	12 to 18
C1[5]	1 to 2	60 to 70	70 to 90	100 to 150	0 to 15
	1 to 2⅕	70 to 80	70 to 90	100 to 150	3 to 20
C2[5]	1 to 1⅘	70 to 75	70 to 90	150 to 200	0 to 12
	1 to 2	75 to 80	70 to 90	150 to 200	5 to 20
V1[5]	1 to 2⅛	60 to 70	70 to 90	100 to 150	0 to 20
	1 to 2¼	70 to 80	70 to 90	100 to 150	1 to 25
V2[5]	1 to 2⅛	70 to 75	70 to 90	150 to 200	5 to 20
	1 to 2¼	75 to 80	70 to 90	150 to 200	5 to 25

[1] The recommended proportions of glue and water are in general suitable for both lumber and veneer gluing but ordinarily it is better to use thicker glue mixtures with lumber than with veneer.

[2] Wood pieces laid together as soon as spread with glue.

[3] Weight of wet glue mixture.

An animal glue equivalent to about a No. 12 in the National Association of Glue Manufacturers grades. Other grades may be used by making suitable adjustments in the glue-water proportion.

[5] Average prepared casein and vegetable glues; some commercial glues require more or less water to obtain the same consistency of mixture.

TABLE 8.—*Index of gluing schedules for different woods*

[H=heartwood; S=sapwood; M=heartwood and sapwood mixed]

Species	Animal glue	Casein glue	Vegetable glue
	Schedule	*Schedule*	*Schedule*
Alder, red M	A2	C1	V1
Ash H	A3	C2	V2
Do S	A3	C2	V2
Basswood M	A3	C2	V1
Beech H	[1] A3	[1] C2	[1] V2
Do S	A3	C2	V2
Birch H	[1] A3	[1] C2	[1] V2
Do S	A3	C2	V2
Butternut M	A2	C2	V1
Cedar, Alaska M	A2	C2	V2
Cedar, eastern red H	[1] A3	C1	V1
Do S	A2	C1	V1
Cedar western red H	A1	C1	V1
Cherry, black H	A3	C2	V2
Chestnut M	A1	C1	V1
Cottonwood M	A2	C2	V1
Cypress, southern H	A3	C1	V1
Do S	A1	C1	V1
Douglas fir H	A1	C2	V1
Elm, American M	A3	C2	V2
Elm, rock M	A3	C2	V2
Fir, white M	A1	C1	V1
Gum, black H	[1] A3	C2	[1] V2
Do S	A3	C2	V2
Gum, red H	[1] A3	[1] C2	[1] V2
Do S	A3	C2	V2
Gum, tupelo H	[1] A3	C2	V2
Gum, tupelo S	A3	C2	V2
Hemlock, western M	A1	C1	V1
Hickory M	A3	[1] C2	V2
Magnolia H	A3	C2	V2
Do S	A3	C2	V2
Mahogany H	A2	C2	V2
Maple, soft (commercial) M	A3	C2	V2
Maple, sugar M	A3	C2	V2
Oak, red M	A3	C2	V2
Oak, white M	A3	C2	V2
Osage orange H	[1] A3	[1] C2	[1] V2
Pecan H	A2	C2	V2
Persimmon S	A3	C2	V2
Pine, northern white M	A1	C1	V1
Pine, southern yellow M	A2	C2	V2
Pine, western yellow M	A2	C1	V1
Poplar, yellow M	A2	C2	V1
Redwood H	A1	C1	V1
Sassafras M	A2	C2	V2
Spruce M	A1	C1	V1
Sycamore M	A3	C2	V2
Walnut, black M	A3	C2	V2

[1] Treatment of the wood before gluing as described on page 48 is recommended where the strongest possible joints are required.

The schedules recommended in Table 8 apply where maximum strength of joints is of chief importance and may be in some cases stricter than required.

In preparing the above schedules no attempt was made to list all the combinations of conditions which give good results or to cover all the conditions which exist in factory operations. For example, the temperature of the wood may in summer be as high as 80° or 85° F., and at the same time the character of the gluing operation may require an assembly time as short as one-half minute. In gluing such a species as birch with animal glue, other conditions shown in Schedule A3 must then be changed. In this case, a glue, which is one grade higher in jelly strength, mixed 2 parts water to 1 part glue (footnotes 1 and 4, Table 7), and a pressure of 100 pounds per square inch will give satisfactory results.

Necessary prerequisites in all the schedules recommended are properly dried and machined wood, glue spreaders which spread the glue evenly, and presses that apply pressure uniformly over the joint.

PRINCIPLES OF GLUED-WOOD CONSTRUCTION

CROSS-BANDED CONSTRUCTION

Cross-banded construction comprises a large class of products consisting of two or more layers of wood glued up with the grain of one or more layers at an angle (usually 90°) with the others. Plywood is a term generally used to designate a cross-banded construction where all plies are thin. The term veneered panels generally refers to a cross-banded construction with a core of lumber and with one or more layers of veneer on each face. Several types of plywood and veneered panels are shown in Figure 3.

Plywood and veneered panels are usually three or five ply. In a 3-ply construction the two outside plies are called faces and are usually laid at right angles to the grain of the center ply or core. (Fig. 3, A and B.) In 5-ply panels the outer plies are again called faces, or face and back, the second and fourth plies are the cross-bands, and the center ply is the core. (Fig. 3, C and D.) In a 5-ply construction the grain of the cross bands is usually at right angles to the grain of the face, back, and core. Plywood construction other than three or five ply may be used, but an odd number of plies is generally employed. (Fig. 3, E and F.) The core, over which the face and cross-banding veneers are laid, may be of veneer, of lumber, or of various combinations of veneer or lumber as shown in Figure 3, A, B, I, and J. Panels may range in total thickness from less than one-sixteenth of an inch to more than 3 inches. They may vary as to shape, number, and thickness of the different plies, and as to the kinds and the combinations of woods used.

As compared with solid wood, the chief advantages of cross-banded construction are marked resistance to checking and splitting; greater uniformity in strength properties with the width and length of the panels; less change in dimensions under changes of moisture content; and, in the case of properly constructed panels, less liability to warp (*18*).

A piece of lumber or veneer will withstand a greater stress along the grain than across the grain. The strength along the grain is usually greater than necessary, and the strength across the grain is often less than desired. When pieces are glued together with the direction of their grain at right angles, each piece helps the other resist stresses across the grain, and their strengths in the two directions, are, in effect, averaged. The result is a more homogeneous product than solid wood.

Similarly, since the tendency to shrink and swell with moisture changes is very slight along the grain, the crossing of the plies counteracts the normal shrinkage and swelling of the wood across the grain, and, therefore, the glued cross-banded product under varying moisture conditions is nearly constant in width and length. Furthermore, it is not necessary that the cross plies, such as the core in a 3-ply or the crossbands in a 5-ply veneered panel (fig. 3) be thick or that they occupy a very large part of the total thickness of the cross-banded product. For example, in a 5-ply, thick-core panel one twenty-fourth + one-twentieth + thirteen-sixteenths + one-twentieth + one twenty-fourth of an inch, the $\frac{1}{20}$-inch crossbands restrain the core and face plies from shrinking or swelling appreciably with moisture changes. The thickness of a cross-banded panel, however, can change as it would if it were made from solid wood since there is no restraining force in the direction of thickness.

To realize fully the advantages of cross-banded construction the panels must be properly designed and glued. The tendency of panels to warp and twist may be even greater in improperly constructed plywood and veneered panels than in the average solid wood of the same thickness. Therefore, in cross-banded construction where the movement of the wood is prevented when it loses or absorbs moisture, large stresses are set up. The adjoining plies try to shrink or swell in directions which are at right angles to each other, but each ply restrains the ply or plies next to it. The contending forces, therefore, tend to break the glue joint or to distort the panel. The development of these stresses can not be prevented if the moisture content of the wood changes, but their effect can be largely controlled by proper design and well-glued joints.

In cross-banded products that are properly designed, the forces exerted by the plies on one side of the core under changing moisture conditions balance in magnitude and in direction the forces exerted by the plies on the other side of the core. This balance is partly accomplished by the use of an odd number of plies so arranged that for any ply on one side of the core there is a corresponding parallel ply on the other side at the same distance from the core. (Fig. 3.) If only two plies are glued together with the grain at right angles to each other, each ply tends to distort the other when moisture changes occur, and cupping of the panel results. On the other hand, two or more adjacent plies with the grain parallel have much the same effect as a single ply with a thickness equal to their combined thickness. For example, a 3-ply panel, with the grain of two adjacent plies parallel but at right angles to the third ply will cup the same as a 2-ply panel when both are subjected to moisture changes. If, however, a fourth ply parallel and similar in properties to the one single ply is glued as a face to the parallel plies face the construction is balanced and in effect three ply.

Corresponding plies should not only exert their forces in the same direction, but the forces should be of the same magnitude. The forces exerted by two otherwise similar plies are proportional to their thickness. There is a practical limit to the allowable thickness of the face plies, however, because thick veneers exert larger stress than thin plies so that even strong joints may fail when thick face-plies are used. This is especially true for the high-density woods. A 3-ply panel with faces of unequal thickness but otherwise alike will become concave on the thicker side when dried. When moist, the panel of the same type construction will become convex on the thicker side. Unequal sanding of the face plies of a panel produces an effect similar to the use of faces of unequal thickness.

In addition to being correctly spaced from the core, the wood used in corresponding plies should be of the same shrinkage and density to obtain a balanced effect. The shrinkage of wood varies with the species, with the method of cutting, and with the density. In some woods there is as large a difference in shrinkage between the quartered-grain wood and the rotary-cut flat-grained wood of the same stock as there is between woods of different species. Consequently, flat-grain and quartered material of the same wood may not balance each other as closely as is possible with different woods. For the best results, therefore, pieces from the same species should be used which are of similar density and which are cut in the same manner.

Table 9 shows the average shrinkage and density of woods commonly used for plywood and veneered panels. Shrinkage data for quartered (radial) and rotary-cut (tangential) stock are shown since some species are manufactured and used extensively in both forms. The table should enable one to select species which have about the same percentage of shrinkage and density. Differences in density between two woods can theoretically be compensated for by varying the thicknesses of the plies in inverse proportion to their specific gravities. This method of compensation would result in using a proportionately thicker ply of the lighter species, which may be advantageous in some cases. The practice, however, is not common.

TABLE 9.—*Average shrinkage and density of woods commonly glued*[1]

Species	Shrinkage [2]		Density [3]	Species	Shrinkage [2]		Density [3]
	Tangential	Radial			Tangential	Radial	
	Per ct.	*Per ct.*			*Per ct.*	*Per ct.*	
Mahogany (*Swietenia* sp.)	4.7	3.4	0.48	Shortleaf pine	8.2	5.1	0.54
Northern white pine	5.9	2.2	.39	Red oak	8.3	3.9	.63
Western yellow pine	6.4	3.9	.41	White ash	8.7	5.3	.64
Chestnut	6.7	3.4	.44	Yellow birch	9.0	7.4	.63
Yellow poplar	6.9	4.1	.41	White oak	9.0	5.3	.69
Black cherry	7.1	3.7	.51	Cottonwood	9.2	3.9	.43
Black walnut	7.1	5.2	.57	Sugar maple	9.2	4.8	.62
Red alder	7.3	4.4	.42	Basswood	9.3	6.6	.38
Sycamore	7.6	5.1	.50	American elm	9.5	4.2	.51
Tupelo gum	7.6	4.2	.52	Red gum	9.9	5.2	.49
Douglas fir (west coast)	7.9	5.0	.44	Beech	10.6	4.8	.63
Red maple	8.1	3.8	.54				

[1] Data, except mahogany, from U. S. Dept. Agr. Bul. 556 (*37*).
[2] Shrinkage from green to oven-dry condition expressed in per cent of dimensions when green.
[3] Density expressed as specific gravity based on oven-dry weight and air-dry volume.

Opposite plies to be symmetrical and balanced must have about the same moisture content when glued. Variations in moisture content of corresponding plies at the time of gluing bring about shrinkage differences that result in warping. Large changes in the moisture content of the wood after gluing should be avoided as much as possible because they induce internal stresses of large magnitude and cause warping, checking, and weak joints.

The use of cross-grained veneer is one of the most common causes of warping and cupping in cross-banded construction. Deviations in the grain of only 5° to 10° from straight cause considerable distortion. While it is impossible to eliminate all cross-grained veneer, that which shows an excessive amount of cross grain should be rejected in plywood manufacture or used in such a manner or for such purposes that its effect is not harmful.

Figured veneer, cut from burls, crotches, stumps, and similar growth irregularities is not straight grained but is used because of its desirable appearance. It shrinks with both the width and length of the sheet, whereas a plain veneer shrinks chiefly in one direction. This difference in shrinkage between these two types of veneer causes warping when they are used together in thin panels. With such veneer it is not practical to have a strictly balanced construction, and the effects of such unsymmetrical arrangement must be compensated for in some other way. Ordinarily, by laying figured veneer of this kind over a thick and properly cross-banded core the construction is made resistant enough against warping to prevent the unbalanced forces of two thin faces from excessively distorting or warping. In gluing thick 5-ply veneered panels (fig. 3, D) this construction makes it possible to use a figured veneer on the panel face and a straight-grained veneer on the panel back.

It is especially important that the crossbands should be of good quality, for they particularly affect the shape and permanence of the form of the panel. They should be straight grained and smoothly cut and should be of sound wood which is even in grain and texture. Imperfections in the crossbands, such as marked differences in the texture of the wood or irregularities in the surface, are easily seen in the panel through thin surface veneers. This is especially true in highly polished panels which have a conspicuous grain in the crossbands. The warping of thick 5-ply panels is commonly the result of using cross-grained veneer in one or both of the crossbands, which shrinks and swells abnormally lengthwise. A very small change in the length of one crossband allows the panel to become distorted. Where the grain runs diagonally across both sheets of veneer, the warping is very pronounced unless the crossbands are laid with the grain parallel to each other.

REQUIREMENTS FOR CORES

Where the crossbands and face veneer are relatively thin, the cores for high-grade panels must be practically free of knots, limb markings (local areas of cross grain occurring in the region of knots), and doty and decayed wood. Unless removed, such defects may be visible on the faces of panels after they have received a finish. The size of defects that may be allowed in cores without showing upon the finished faces depends largely on the thickness of the crossband

and face veneers. Prevailing commercial practice varies as to the maximum size of knots and blemishes permitted, but in general it is from one-fourth to one-half of an inch in diameter. Doty and decayed wood have a different shrinkage from sound wood and under moisture changes this shrinkage difference may become noticeable on highly finished surfaces.

The best core woods for high-grade panels are of low density, of low shrinkage, of slight contrast between the spring wood and the summer wood, and of the species which are easily glued (*52*). Edge-grained cores are better than flat-grained cores because of their low shrinkage in width, and, in softwoods with pronounced summer wood they are better for the additional reason that the hard bands of summer wood are less likely to show through thin veneer in edge-grain lumber than in the flat-grained lumber. In most species a core made of all quarter-sawed or all flat-sawed material remains more uniform in thickness with moisture-content changes than one made by combining these two types of material. This advantage is not of great practical significance, however, where the laminations are narrow and the glue joints are strong. In addition to its properties, the cost price, the percentage of clear cuttings, and the quantity available generally determine the extent to which a wood is used for cores. Yellow poplar and chestnut are deservedly popular core woods. Basswood and the gum woods are also extensively used for cores.

The use of the chestnut, which is a very desirable core wood, deserves special mention. This wood is now being forced on the market because of the ravages of a chestnut blight which is slowly exterminating the species. Because of lack of a good market, much of the dead chestnut timber is being left in the woods to rot despite the fact that the wood from dead trees, so long as it is not decayed, is in every way as good as that from live trees. Manufacturers who use chestnut wood are therefore salvaging a wood that might otherwise be wasted.

White pines, western yellow pine, and Douglas fir are woods that are used very largely for cores in doors. Such cores are commonly built from small pieces of wood which are incident to the manufacture of sash and other millwork and are faced with thick veneers. However, for cores in high-grade veneered panels the coniferous woods which have pronounced summer wood must be used with discretion to prevent their growth rings from showing through the finished face veneers.

PARALLEL GRAIN CONSTRUCTION

Parallel-grain or laminated construction, as distinguished from cross-banded construction, refers to two or more layers of wood fastened together with the grain of all layers approximately parallel. The size, shape, number, and thickness of the laminations or plies may vary greatly. (Fig. 17.) Parallel-grain construction may be used as a base for veneer, as in cores for doors, table tops, and other furniture panels, or it may be used unveneered, as in automobile sills, steering-wheel rims, porch columns, airplane propellers, and wooden pulleys.

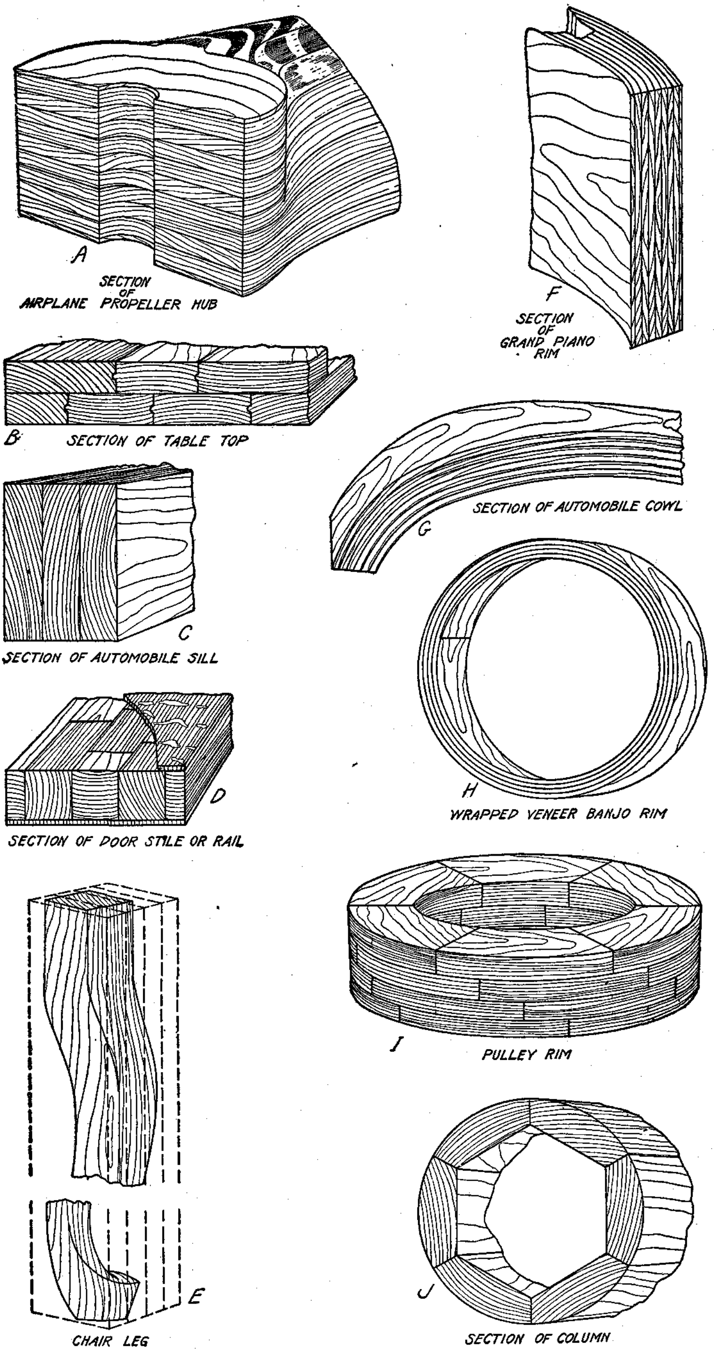

FIGURE 17.—Types of parallel-grain construction: *A*, Section of airplane propeller hub; *B*, section of table top; *C*, section of automobile sill; *D*, section of door stile or rail; *E*, chair leg; *F*, section of grand piano rim; *G*, section of automobile cowl; *H*, wrapped veneer banjo rim; *I*, pulley rim; *J*, section of column

While the properties of parallel-grain products are generally similar to those of solid wood, the gluing of them together makes it possible to manufacture wide or thick articles out of smaller and cheaper material and generally with less waste of wood than if solid wood alone were used. For example, glued table tops can be made in widths which it is impossible to obtain from most species in solid wood. Such articles, if well constructed, are less likely to warp and check than if made of a single wide board. Curved members (fig. 17, F, G, and H) can be made either by pressing or wrapping thin laminations around curved forms or by gluing the individual segments together. (Fig. 17, I and J.) On account of the direction of the grain of the wood in these products, their strength is far superior to solid wood cut to the same size and shape.

Differences in shrinking or swelling are the fundamental causes of internal stresses and laminations should be of such character that they shrink or swell the same amounts in the same directions. The laminations should therefore be straight grained, of the same shrinkage properties (Table 9), and at the same moisture content when glued. Lengthwise shrinkage in a straight-grained piece of normal wood is only about one-third of 1 per cent, while the shrinkage sidewise may be ten or twenty times as much. In a cross-grained lamination the shrinkage across the grain changes the length of the piece more than the normal amount and consequently sets up stresses in long pieces which may cause serious warping.

If two or more pieces having different shrinkage properties are glued together, even though they are straight grained, a moisture change will cause them to shrink or swell different amounts and thus set up stresses. If internal stresses are to be avoided, flat-grained wood should not be glued to edge-grained wood, nor should different species be glued together unless they have similar shrinkage properties.

Combining pieces at different moisture content results in stresses when they later come to a common moisture content. The pieces should therefore be conditioned to about the same moisture content before being glued.

The relative density of the different pieces of the same species in parallel-grain construction is not very important, as test specimens show little weakening or warping from this cause (*26*).

In making glued parallel-grain articles it is important to avoid as much as possible the development of internal stresses when the article is exposed to conditions which change its moisture content. In an article like an airplane propeller, where extreme refinement of shape and balance is necessary, the greatest precautions against internal stresses must be observed. However, in gluing ordinary articles, especially in edge-to-edge gluing, moderate attention to shrinking and swelling will be sufficient.

The stresses which develop in parallel-grain articles due to differences in the properties of the various members will gradually disappear if the glued article is kept for a long time at a constant moisture content. This is because the stressed members, stretch, check, or warp until all of the stresses are relieved. Stresses due to moisture differences in the wood at the time of gluing will not reäppear after having once been relieved. Stresses due to cross grain or to differences in the shrinkage properties of the adjacent members will reappear if the moisture content is changed after having once been relieved.

BUTT-JOINT CONSTRUCTION

Butt joints are those in which the end grain of two pieces of wood is glued together or the end of one piece is glued to the side of another. Mitered joints chiefly present end grain and are therefore considered butt joints. Several types of butt joints are shown in Figure 2.

It is practically impossible to make square end-butt joints sufficiently strong or permanent enough to meet the requirements of ordinary service. The gluing of end-grain joints is more difficult than the gluing of side-grain joints, and the stress placed upon them in service is more severe. Tests made in gluing end-grain surfaces have shown that such joints are erratic and in strength they rarely exceed 3,000 to 4,000 pounds per square inch. With the most careful gluing possible not more than about 25 per cent of the tensile strength parallel with the grain can be obtained.

In order to obtain good strength in pieces spliced together endwise, it is necessary to make a scarf, fingered, serrated, or other sloped joint. (Fig. 2, B and C.) To make the joint as strong as the wood, it is necessary to have the slope not steeper than the proportion of 1 across the grain to 8 along the grain, and longer slopes are necessary for species which are of high strength or which are not easy to glue. The plain scarf joint is perhaps the easiest to glue, and it also involves fewer machining difficulties than are involved in the sharply angular forms. In tests on plain scarf joints the following slopes were found necessary to produce joints as strong in tension[32] along the grain as the solid wood of the species tested:

Species	Slope
Yellow poplar	1 in 8
Red gum	1 in 8
Mahogany	1 in 10
Yellow birch	1 in 12
Red oak	1 in 15
White oak	1 in 15
Black walnut	1 in 15

It is practically impossible to make permanent plain end to side grain joints (fig. 2, D) where strength is important because it is not only difficult to make a good glued joint on end-grain wood but when such a joint is made the stresses to which it is subjected in service are unusually severe. Under changing moisture conditions the end-grain piece of the joint tends to swell or shrink considerably along both dimensions of the joint while the side-grain piece of the joint swells or shrinks only in one direction. Joints which are not subjected to much external stress may serve satisfactorily; for example, the joints made by gluing facing strips of veneer on the end edges of a cross-banded table top. (Fig. 3, K.) In chair backs and other furniture parts, however, the stresses placed on end to side grain joints by the service to which they are put are very severe, and, when combined with the internal stresses due to moisture changes, usually re-

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[32] In bending tests on scarf joints in Sitka spruce a slope of 1 in 10 was found necessary to make the joint as strong as the wood (*20*).

sult in the ultimate failure of the joint. It is therefore necessary in the manufacture of such parts to use irregular shapes of joints, dowels, tenons, and other devices (fig. 2) in order to reinforce the joint or to secure a larger gluing area, but even then the stresses which recur with seasonal changes put a very severe test on the joints. It is very desirable to protect such glued joints against moisture changes. The strength and permanence of all types of end-to-side-grain joints depend upon the accuracy of the machining and upon the fit of the parts as well as upon their design. There are no adequate data, however, on the comparative strength of different designs.

CORRECTING GLUING DEFECTS

Every woodworking plant should have a competent personnel to detect the causes of gluing defects and to correct them. Serious gluing defects usually result from a combination of causes and are therefore seldom due entirely to a single condition. Without a full knowledge of the manufacturing process it is not always possible to tell by inspecting a defective sample just what has caused the difficulty. Furthermore, the same general type of defect may be caused by entirely different conditions. It is not possible to present a complete key to the causes and remedies for all gluing defects. A number of the more common defects are listed below, however, together with some of their usual causes.

KEY TO CAUSE OF GLUING DEFECTS

1. Open glue joints. Some of the causes are the following:
    - A. Weak joints, as a result of—
        - (1) Incomplete contact, due to—
            - (*a*) Improper machining of pieces (p. 16)—
                - Uneven thickness.
                - Irregular surfaces.
                - Poorly fit joints.
                - Tooth planing.
            - (*b*) Wrong condition of glue at time of pressing—
                - Dried or jellied glue (p. 37).
                - Foamy glue (pp. 10 and 24).
                - Uneven spread of glue (p. 23).
            - (*c*) Insufficient pressure (p. 24)—
                - Warped stock.
                - Jellied glue.
                - Uneven application of pressure (p. 26).
                - Unevenness of press plates or cauls (pp. 26 and 27).
        - (2) Contact complete but joints weak, due to—
            - (*a*) Character of glue—
                - Low strength (p. 4).
                - Mixed too thin (p. 10).
                - Partially dissolved (p. 10).
            - (*b*) Insufficient glue spread (p. 41).
            - (*c*) Starved joints (pp. 37 to 40), caused by—
                - Excessive heating of wood.
                - Too thin glue mixture.
                - Quick clamping.
                - Excessive pressure.
            - (*d*) Oil, wax, or other material on wood.
            - (*e*) Pressing period too short (p. 27).
            - (*f*) Exposure of nonwater-resistant glues to moisture.

1. Open glue joints—Continued.
   - B. Improperly dried or conditioned lumber, as a result of—
     - (1) Too high or too low moisture content (p. 14).
     - (2) Moisture contents not uniform (p. 15).
   - C. Improper design, as a result of—
     - (1) Thick plies (plywood construction) with the grain at right angles (p. 54).
     - (2) End-grain joints not properly reinforced (p. 59).
2. Blisters. Some of the causes are the following:
   - A. Uneven thickness of stock (p. 16).
   - B. Incomplete contact, as a result of irregular spread of glue (p. 23).
   - C. Poor cauls (p. 26).
   - D. Too short pressing time (p. 27).
   - E. Steam pockets (in hot pressing) (p. 29).
   - F. Causes listed under 1.
3. Warping. Some of the causes are the following:
   - A. Unbalanced construction, as a result of—
     - (1) Corresponding plies not parallel or at right angles to adjacent plies (p. 53).
     - (2) Corresponding plies of unequal thickness, sanding, shrinkage, density, or moisture content (pp. 54 to 55).
   - B. Cross-grained or decayed wood in crossbands or cores (pp. 55 and 56).
   - C. Gluing together pieces of unequal or incorrect moisture content (p. 58).
   - D. Improper drying after gluing, as a result of—
     - (1) Drying conditions too severe (p. 29).
     - (2) Final moisture content too low (p. 32).
     - (3) Stickers improperly placed or insufficient in number.
     - (4) Unequal or incomplete drying.
   - E. Bending in press and clamps (p. 27).
   - F. Uneven moisture changes through finish on face and back.
4. Surface defects, such as:
   - A. Checks, as a result of—
     - (1) Finishing before wood has dried to proper moisture content.
     - (2) Wood glued at too high a moisture content (p. 14).
     - (3) Too much moisture added in gluing (p. 15).
     - (4) Drying conditions too severe (p. 29).
     - (5) Internal stresses.
     - (6) Improper construction, due to face plies and adjacent underplies parallel.
     - (7) Assembly time too long (p. 38).
     - (8) Poorly cut veneer (p. 19).
   - B. Sunken joints, as a result of surfacing before glue moisture is dried out or distributed (p. 31).
   - C. Corrugated appearance, as a result of—
     - (1) Planer marks on core or crossband (p. 17).
     - (2) Using cores or crossbands of very contrasted grain (p. 55).
     - (3) Uneven moisture content in core lumber before gluing (p. 15).
   - D. Uneven spots, as a result of—
     - (1) Knots, limb markings, or bruises in core or crossbands (p. 55).
     - (2) Open joints or laps in crossbands.
     - (3) Uneven spread of thick glue under faces or crossbands.
     - (4) Blisters (see 2).
   - E. Staining, as a result of—
     - (1) Alkaline glues (Table 1 and p. 49).
       - (*a*) Veneer glued too wet (p. 16).
       - (*b*) Left in clamps too long (p. 29).
     - (2) Use of too thin face veneers with dark-colored glue (p. 48).
     - (3) Use of wood which was discolored before gluing.
     - (4) Too high temperatures in pressing panels.

APPENDIX

GLUE FORMULAS

The following glue formulas, with directions for mixing, were developed at the Forest Products Laboratory by the laboratory personnel and are available for the free use of the people of the United States.

CASEIN GLUE FORMULA NO. 11[33]

Ingredients

	Parts by weight
Casein	100
Water	220 to 230
Hydrated lime	20 to 30
Water	100
Silicate of soda	70
Copper chloride	2 to 3
Water	30 to 50

The 220 to 230 parts of water added to the casein is approximately the right amount to use with Argentine (naturally soured) casein; but if a different casein is used the water requirement will lie somewhere between 150 and 250 parts by weight. The correct amount for different caseins must be determined by trial.

The formula presupposes that a high calcium lime will be used. A lime of lower grade may be used, but a proportionately larger amount of it will be needed, or the water resistance of the glue will be sacrificed. It is suggested that for the first trial the user try 25 parts of lime. If this does not give good results the amount can be varied within the limits specified.

The density of the silicate of soda used should be about 40° Baumé, with a silica-soda ratio of from 3 to 3.25.

Copper sulphate can be substituted for copper chloride.

Place the casein and water in the bowl of the mixing machine and rotate the paddle slowly, stirring the mixture until all the water has been absorbed and all the casein moistened. If the casein is allowed to soak beforehand it is more readily dissolved in the mixing process. Mix the hydrated lime with water in a separate container. Stir this mixture vigorously at first, but just before it is added to the casein stir just enough with a gentle rotary motion to keep the lime in suspension. Pour the milk of lime quickly into the casein.

When casein and lime are first combined they form large, slimy lumps, which are balls of dry casein coated with partly dissolved casein. These break up rapidly, becoming smaller and smaller, and finally disappear. The solution, in the meantime, is becoming thin and fluid. At this point stop the paddle and scrape the sides and bottom of the container, and then stir again. If a deposit of casein remains unacted on, it may cause more lumps later.

When about two minutes have elapsed since the lime and casein were united, it may be noticed that the glue has begun to thicken a little. Add the sodium silicate now, or else the glue will become too thick. The glue will momentarily become even thicker, but this thickness will soon change to a smooth and fluid consistency.

Continue the stirring until the glue is free from lumps. This should not take more than 15 or 20 minutes from the time the lime was added. If the glue is a little too thick, add a small amount of water. If the glue is too thin, it will be necessary to start over again, using a smaller proportion of water.

The copper salt may be added at any one of several times during the mixing process. If added as a powder before the casein is soaked, it may have a corrosive action upon the metal container. The copper salt, if added as a powder, should be thoroughly mixed with the casein before the addition of the lime. Copper salt may be placed in solution and conveniently stirred into the moistened casein immediately before the lime is added or after all the other ingredients have been combined. If the copper solution is added at the end of the mixing period, pour it into the glue in a thin stream and stir the mixture vigorously. Continue stirring until any lumps, which may have formed by the

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[33] BUTTERMAN, S., and COOPERRIDER, C. K. Op. cit.

coagulation of the glue and the copper solution, are broken up and until a smooth violet-colored glue is obtained.

Glue prepared by formula No. 11 has proved to be exceptionally strong and durable, even under wet or damp conditions.

CASEIN GLUE FORMULA NO. 4B[33]

Formula No. 11 as above specified but without the copper solution represents an earlier stage of casein-glue development, known as formula No. 4B. The mixing is the same as for formula No. 11 except for the omission of the copper chloride. The glue made by formula No. 4B has a medium consistency, excellent working properties, a good working life, and makes joints of high strength, but it falls somewhat short of formula No. 11 in water-resisting properties, especially when the lower amounts of lime are used.

CASEIN GLUE FORMULA NO. 20

Ingredients	Parts by weight
Casein	100
Water	200
Sodium hydroxide (caustic soda)	10
Water	50

Bring the casein and water together according to the directions for mixing glue prepared by formula No. 11. Dissolve the caustic soda in water in a separate container, and while the mixing paddle is revolving sprinkle the caustic-soda solution into the damp casein. Stir slowly until a thin, smooth glue has been obtained. The consistency of the finished product may be altered by adding more casein if it is too thin, or by adding water if it is too thick. Silicate of soda is sometimes added to thicken or to reduce the cost of the glue per unit of volume.

This glue has exceptional strength when dry, but when exposed to moisture it weakens as rapidly as animal or vegetable glue.

BLOOD-ALBUMIN GLUE—HOT PRESS FORMULA[34]

Ingredients	Parts by weight
Blood albumin (90 per cent solubility)	100
Water	170
Ammonium hydroxide (specific gravity 0.90)	4
Hydrated lime	3
Water	10

Pour the larger amount of water over the blood albumin and allow the mixture to stand undisturbed for an hour or two. Stir the soaked albumin until it is in solution and then add the ammonia while the mixture is being stirred slowly. Slow stirring is necessary to prevent foamy glue. Combine the smaller amount of water and the hydrated lime to form milk of lime. Add the milk of lime, and continue to agitate the mixture for a few minutes. Care should be exercised in the use of the lime, inasmuch as a small excess will cause the mixture to thicken and become a jellylike mass. The glue should be of moderate consistency when mixed and should remain suitable for use for several hours. The exact proportions of albumin and water may be varied as required to produce a glue of greater or less consistency or to suit an albumin of different solubility from that specified.

PARAFORMALDEHYDE-BLOOD-ALBUMIN GLUE FORMULA[35]

This formula produces a blood-albumin glue, which may be pressed either hot or cold.

Ingredients	Parts by weight
Blood albumin (90 per cent solubility)	100
Water	140 to 200
Ammonium hydroxide (specific gravity, 0.90)	5½
Paraformaldehyde	15

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[33] BUTTERMAN, S. Op. cit. [34] HENNING, S. B. Op. cit. [35] LINDAUER, A. C. Op. cit.

Cover the blood albumin with the water and allow the mixture to stand for an hour or two, then stir slowly. Next, add the ammonium hydroxide with more stirring. Then sift in the paraformaldehyde powder while stirring the mixture rapidly. Paraformaldehyde should neither be poured in so rapidly as to form lumps nor so slowly that the mixture will thicken and coagulate before the required amount has been added.

The mixture thickens considerably and usually reaches a consistency where stirring is difficult or impossible. However, the thickened mass will become fluid again in a short time upon standing at ordinary room temperatures and will return to a good working consistency in about an hour. It will remain in a good working condition for six or eight hours, but when the liquid finally sets and dries, as in a glue joint, it forms a hard, insoluble film.

When the glue is pressed cold it has only moderate strength, and therefore this glue should not be used where maximum strength is required. If hot pressed, however, this glue is high in strength and very water resistant.

WATER-RESISTANT ANIMAL GLUE FORMULA [36]

Ingredients	Parts by weight
Animal glue	100
Water	225
Oxalic acid	5.5
Paraformaldehyde	10

Soak the glue in the water until the granules or flakes have been softened. Melt the glue at about 140° F., and after that lower the temperature to between 105° and 115°. Mix the small crystals of oxalic acid and the powdered paraformaldehyde together, and add the dry mixture to the glue. Stir the mixture until all of the oxalic acid has gone into solution, after which it is ready for use. The paraformaldehyde does not readily dissolve in the glue, and much of it remains as a finely divided solid during the working life of the glue. A certain amount of agitation is, therefore, necessary to keep it evenly distributed throughout the mixture. The paraformaldehyde used should be fine enough to pass through a No. 50-mesh sieve.

The commercial paraformaldehydes for use in this formula should be of the slow-reacting kind. A fast-reacting paraformaldehyde appreciably shortens the working life of the glue mixture.

If kept at a temperature not exceeding 115° F., and when the proper kind of paraformaldehyde is used, the glue will remain in a fluid condition for six to eight hours from the time of incorporating the paraformaldehyde and oxalic acid, after which it will set to a tough, firm jelly which can not be remelted. It is important to avoid heating the glue mixture much above 115° if a long working life is required. Organic decomposition of the glue will not seriously affect the quality of the glue at this temperature, since the chemicals used in preparation also act as preservatives.

Both oxalic acid and paraformaldehyde are poisonous chemicals, and should therefore be handled with care.

This glue combines the usual characteristics of an animal glue, and in addition is highly water resistant. However, the water resistance varies directly with the temperature of the water to which the glued article is subjected. At room temperatures the glue is highly water resistant, but at 140° F. it is very low in water resistance. A conditioning period of about two weeks at ordinary room temperatures should be allowed for the joints to obtain their full water resistance when this glue is used.

TESTING GLUES

TESTS FOR ANIMAL GLUES

JELLY STRENGTH

The jelly-strength test is based upon the assumption that the value of a glue is dependent upon the strength of the jelly formed upon cooling a solution of a given concentration. It is a difficult test to make accurately and its use is

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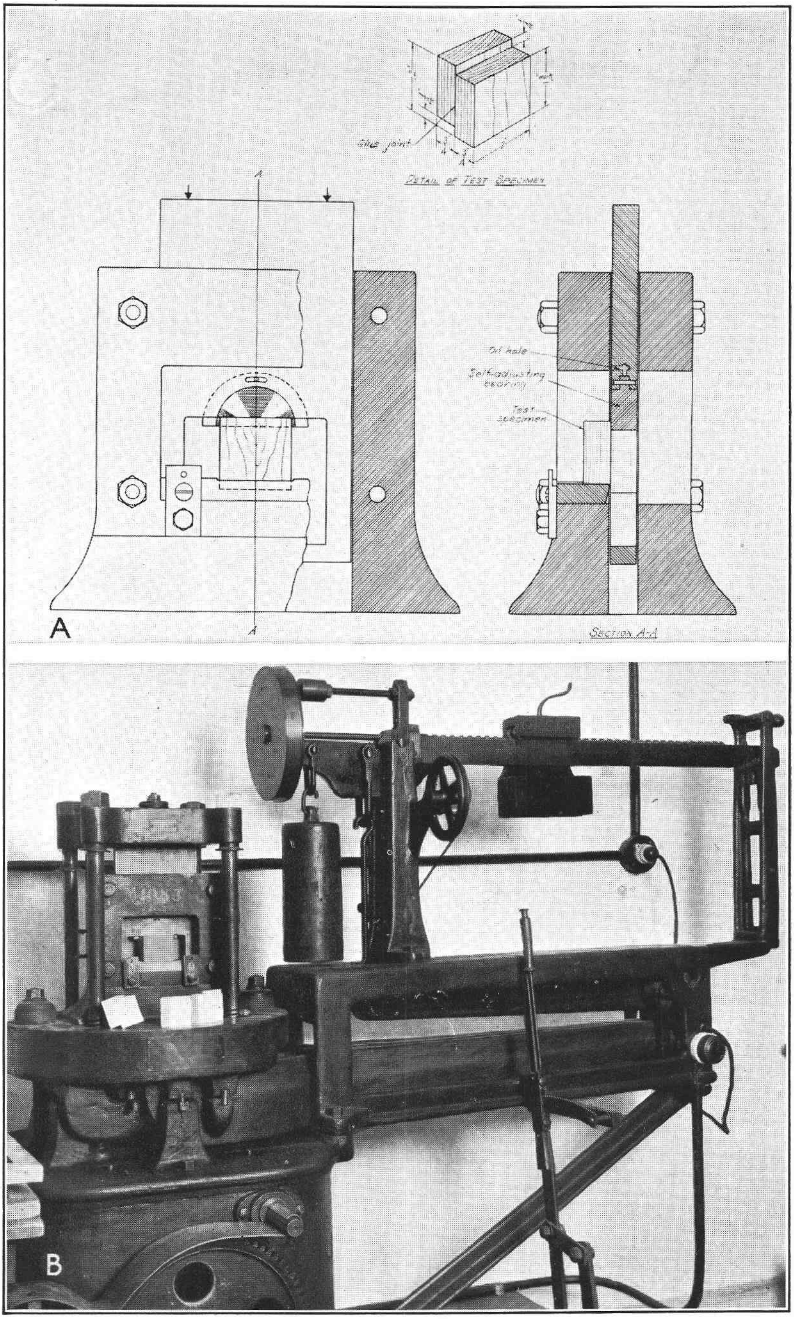
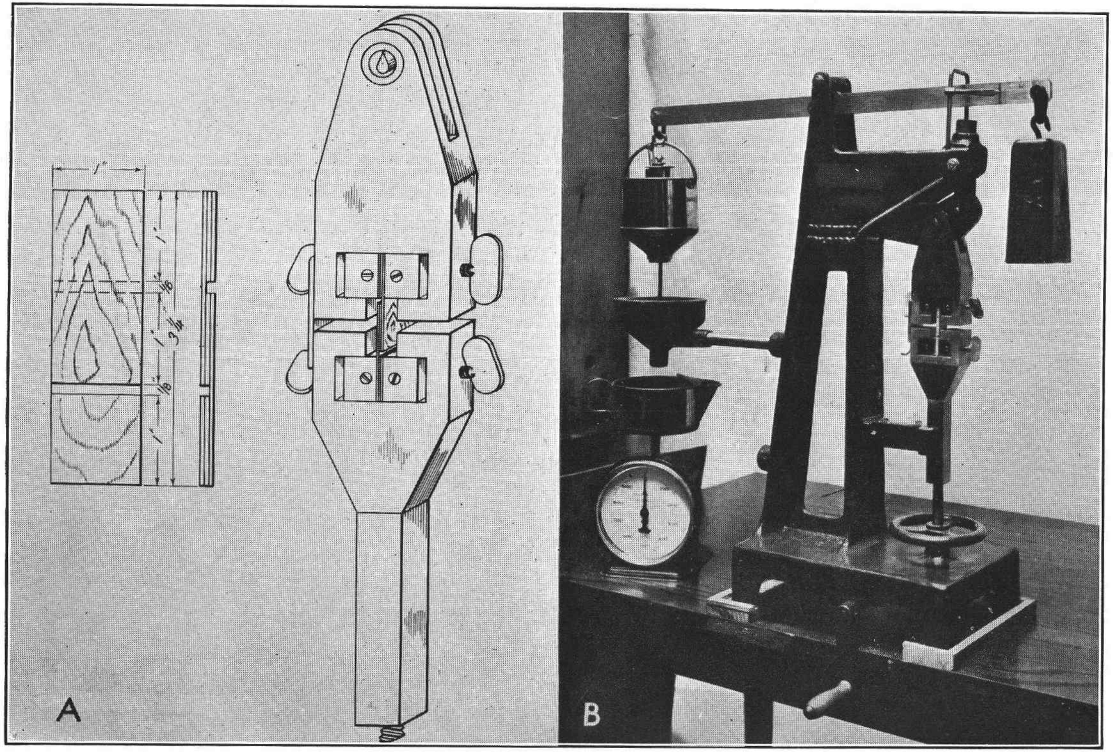
[36] LINDAUER, A. C., and HUNT, G. M. WATER-RESISTANT GLUE. (U. S. PATENT NO. 1506013.) U. S. Patent Office, Off. Gaz. 325: 782. 1924.



EQUIPMENT USED AT FOREST PRODUCTS LABORATORY FOR THE BLOCK SHEAR JOINT TEST

A.—Test specimen and shearing tool.
B.—Testing machine showing test specimen in place.



EQUIPMENT USED FOR THE PLYWOOD-JOINT TEST

A.—Test specimen and grips; B, machine used at the Forest Products Laboratory in testing the joint strength of plywood.

therefore restricted somewhat, especially among glue users, but it can be depended upon to supply information of value.

The modern jelly test consists in preparing a solution of a definite concentration, placing a given amount of the solution in a container of a standard size and shape, allowing the solution to cool at a definite temperature until it forms a jelly, and determining the firmness or elasticity of the jelly. The strength of the jelly may be expressed relatively by comparison with a glue of an arbitrary standard or by numerical units. It is necessary to have suitable equipment and it is important that the solution be chilled at a given temperature for a definite time and tested at the same temperature.

The oldest method employed for measuring the strength of a glue jelly is the finger test. In this test the strengths of two or more jellies are compared empirically by pressing the glues with the fingers. If used in grading glues, it is necessary to compare the unknown glues with an arbitrary standard or set of standards, handling the samples at the same time and in exactly the same manner. This method is the simplest means of measuring jelly strength and with practice may be applied with surprising accuracy. The personal factor and the absence of numerical values are its chief disadvantages.

Numerous instruments have been devised for measuring the jelly strength of a glue (*6*), many of which give numerical values. With some of these instruments a measure is made of the pressure which is required to break the surface or to sink a plunger a given distance into the jelly or to compress a free column of jelly a given distance. In others the distance which a given weight of a definite shape will sink or displace the jelly is observed. In still others the torsional force required to break a column of jelly is measured. These instruments are often difficult or slow to operate, but they afford a numerical basis for judging jelly strength and therefore a means of accurate comparison.

The National Association of Glue Manufacturers has adopted the Bloom gelometer of the plunger type, as a standard instrument and has outlined a procedure for making the test (*17*), which is reputed to give results that can be duplicated in different laboratories. The method outlined, while accurate and doubtless a satisfactory basis for grading glues, can not be regarded as generally applicable by the users of glue unless such users are equipped with a glue laboratory and use glue in considerable quantities. It promises, however, to become a generally accepted standard for properly equipped laboratories.

The jelly strength alone is not always an accurate measure of the value of a glue, for although it usually has a definite relation to viscosity (the other main property upon which grade is based) there are exceptions. The jelly strength of some glues may be higher in proportion to the viscosity than that of other glues. Likewise, certain substances when added to the glue are known to affect its jelly strength (*6*). The jelly test is valuable, however, when used in connection with the viscosity and other tests.

VISCOSITY TEST

The viscosity of a glue is usually determined by allowing a specified amount of glue solution at a given concentration and temperature (usually 140° F.) to flow through an orifice or by measuring the resistance offered by the glue to an object moving through it. As with the jelly test, it is necessary to adopt a standard procedure to secure results of value (*17*). The important points in making the viscosity test are briefly summarized as follows:

(1) A definite, constant concentration of glue solution, calculated on the moisture-free basis.

(2) Approximately constant temperature and time used in melting sample.

(3) A constant temperature of solution at the time of test (140±0.1° F. is recommended).

(4) Accurate measure of time of flow or of the resistance offered by the solution to a moving body.

The measurement of the viscosity of glue should preferably be made on an instrument capable of expressing the result in poises, which is the absolute unit of viscosity. Various types of instruments are capable of doing this if they are correctly calibrated.

For viscosity tests of glue, the capillary-tube type of viscometer is the most commonly used; the simplest form of which is a pipette or a straight glass tube constricted at one end. These viscometers are not always arranged so that the temperature of the glue within them can be controlled and therefore are not always accurate. However, a number of more refined instruments based on flow through capillaries have been devised and give satisfactory results.

The National Association of Glue Manufacturers has adopted an instrument of the pipette type (*17*) which perhaps will become the standard viscosity instrument for glue. Differing in principle from the pipette type are the friction-type viscometers, in which a suspended disk, cylinder, or other object is revolved in the glue or the glue container may be revolved about the suspended object. The resistance of the solution to the passing of the disk or cylinder is indicated directly upon an attached scale.

Some animal glues can not be correctly evaluated by a viscosity test; hence, there is the need for the jelly test. For example, the raw material as well as substances which may be added by the manufacturer affect the viscosity without always having a corresponding effect upon the jelly strength. Viscosity and jelly tests together, however, will usually determine the grade of the glue with sufficient accuracy for all woodworking purposes.

MISCELLANEOUS TESTS

Aside from the jelly strength and the viscosity which form the principal tests upon which animal glue is graded, there are a number of miscellaneous tests which may also be used in judging the quality of a glue.

MELTING AND CONGEALING POINTS

The temperature at which an animal glue will melt or congeal is usually termed the melting or jellying point. Investigators (*44*) have shown that they are not identical, but it is known that either or both have a general relation to the grade of the glue. High-grade animal glues have a relatively higher melting or jellying point than low-grade glues. It has been suggested by Bogue (*6*) that the melting point is controlled by both the jelly strength and viscosity and that no other one test so correctly parallels the actual adhesive strength of a glue as the melting point. However, Alexander (*1*) considers that as a general rule the melting point varies simply as the jelly strength.

Perhaps the greatest drawback to a more extensive use of the melting-point test is the difficulty encountered in measuring the melting point accurately. A gradual change takes place as a soaked glue is warmed or cooled, and it is therefore difficult to determine the exact temperature at which it changes from a solid to a liquid state. The melting or jellying point of a solution used for gluing is of further importance, however, in enabling the consumer to use it properly and to get the best results with any given grade. It generally determines the necessity for warming the wood, the assembly time, and other conditions in the gluing operation.

ODOR AND KEEPING QUALITY

The odor of a glue gives some indication of its source and condition. Glue which has an offensive odor is not considered of the highest quality. A bad odor may be due to the fact that partly decomposed material was used in its manufacture or that the glue itself is decaying. For high-grade joint work it is usually specified that the glue be sweet. The odor of different glues varies considerably, and it is difficult to express the different kinds. It is not usually difficult, however, to determine whether the odor indicates decomposed or sweet glue.

The keeping quality of a glue may be tested by allowing the jelly which is left from the jelly-strength test to stand in the laboratory at room temperature for a number of days. The odor and condition of the glue are noted at intervals. Glues with good keeping qualities will stand several days without developing an offensive odor, or showing any appearance of decomposition. A more vigorous test frequently adopted is to keep the solution in a closed container in an incubator at about 98° F. The glue should remain sweet at least 48 hours under these conditions.

GREASE

For woodworking a small amount of grease in glue is not a serious objection. When glue is to be used in a machine where foaming is liable to occur, a small amount of grease is even desirable, because it tends to prevent foaming. The presence of grease can be determined by chemical means (*25*), but it is ordinarily not necessary to be so exact for a glue for woodworking. A common method of testing for free grease in glue is to mix a little water-soluble dye—for example, methyl violet—with the glue solution and then paint the mixed solution upon a piece of unsized white paper. Grease which is not highly dispersed will show as spots, giving the paper a mottled or spotted appearance. This test permits only a rough comparison between glues and gives no accurate numerical measure of the grease content.

FOAM

Glue which foams excessively is objectionable because air bubbles are liable to get into the joint and thus reduce the area in which the glue is in contact with both faces. Foamy glue is especially undesirable for use in glue spreaders, as the glue is agitated much more than when it is used by hand, and the danger of incorporating air bubbles is greater. A test for the amount of foam in a glue is made by beating the glue solution in a container of specified shape and size for a given time with an egg beater or other form of agitator; then noting the height to which the foam rises and the quickness with which it subsides. The foam should be measured after standing for a few minutes. The solution used in the viscosity test may be used also for foam determination.

ACIDITY AND ALKALINITY

If it is either strongly acid or strongly alkaline, animal glue is likely to deteriorate rapidly. A small amount of acid or alkali is not of itself particularly objectionable, although it has been shown that even slight acidity or alkalinity affects to some extent the viscosity, jelly strength, tendency to foam, and other characteristics (*6*). The test for acidity and alkalinity of glue is easily and quickly made by dipping strips of a chemical indicator, such as litmus paper, in the glue solution and noting any color change. If litmus paper turns red it indicates acid. If it turns blue, alkali is indicated. More sensitive indicators may be selected, or electrometric means may be used with greater accuracy.

ASH AND FOREIGN SUBSTANCES

Tests may also be made to determine the ash content and the presence of foreign substances such as salts, which are at times added to give the glues special properties. Such information, while indicating to some extent the origin, treatment, and history of the glue, can not be regarded as an adequate basis for judging its strength. The amount[37] and character of the ash depend upon the source of the glue, its treatment in manufacture, and the presence of inorganic materials which are sometimes added by the glue manufacturer. The ash content will show the presence of zinc oxide, lead and barium sulphate, calcium carbonate, or other inorganic salts added[38] usually to make the glue line less conspicuous in the joint. Such materials are normally not considered adulterants, and their presence in small quantities does not, of itself, indicate a poor or inferior glue.

MOISTURE CONTENT

Animal glue is a hygroscopic substance, and its moisture content varies with the humidity of the atmosphere surrounding it. The moisture content commonly ranges from 8 to 20 per cent of the dried weight.[39] Because of this

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[37] Fernbach (*19*) gives the ash content of glue as varying from 2 to 8 per cent; Rideal (*41*) finds the usual range from 1.5 to 3 per cent; Alexander (*1*) 3 to 4 per cent; Linder and Frost (*32*) from about 1.5 to 5.5 per cent; and Bogue (*6*) 1 to 5 per cent where no inorganic material has been added directly to the glue.

[38] Bogue (*6*) states that where inorganic materials have been added to give color to the glue the ash content may rise to 10 or 15 per cent. Fernbach (*19*) and Rideal (*41*) state that the ash of a bone glue fuses, is neutral, and contains phosphates and chlorides, and that the ash of hide glues does not fuse, is alkaline, and is generally free from phosphates and chlorides. However, Bogue points out that phosphoric acid is now often added to neutralize the lime used with the hide stock and that the fusing of the ash and the presence of phosphates is no longer a reliable means of distinguishing between the two types of glue.

[39] Fernbach (*19*) gives 8 to 16 per cent; Rideal (*41*) 12 to 18 per cent; Bogue (*6*) 9 to 18 per cent; Teesdale (*49*) 8 to 16 per cent; and Linder and Frost (*32*) 10 to 18 per cent. Bateman and Town (*4*) show that the moisture content varies at a temperature of 80° F., and with relative humidities of 30 per cent to 90 per cent from about 13 to 35 per cent, respectively, and found approximately the same percentage of moisture for two grades of glue. Bogue on the other hand reports a variation of moisture content of about 5 per cent from the lowest to the highest grades of animal glue.

wide variation with the humidity of the atmosphere and of the uncertainty of a constant variation between grades, the moisture-content test is rarely of any direct value in judging the quality of a glue. However, a very low moisture content in animal glue is known to be associated with brittleness and crazing.[40] A knowledge of the moisture content is indirectly of value in preparing solutions for viscosity and jelly-strength tests. Under careful testing methods, moisture-content determinations should be made for this purpose.

PROTEIN CONTENT

Chemical analyses of the protein content of animal glues have been suggested, but they involve highly refined methods and equipment, and their value is very questionable. Even though they should in the future prove to be significant, they probably would not be practical for most woodworkers.

MECHANICAL TESTS

Many attempts have been made to measure the strength of glues in joints. For this purpose metal, porcelain, glass, and other materials (*22, 34*) have been tried, but wood is the material usually employed. A discussion of wood-joint tests will be found later under "Tests for blood-albumin, casein, vegetable-protein, and starch glues." For animal glues, wood-joint tests are secondary in importance to the jelly, viscosity, and other tests. However, joint tests have been used to some extent as supplementary tests in the belief that they supply information that is not obtained from the other tests, such as information on the ability of glue to adhere to the wood substance. They have especially been applied by users of glue for woodworking who have, in general, mistakenly placed greater confidence in the joint tests than in the other forms of tests. The extreme difficulty of making the joint tests accurately and of using the glue to the best advantage, together with the variable properties of wood, make such tests questionable for use in judging even the adhesive quality of an animal glue. Poor gluing may result in weak joints with high-quality glues, while very careful gluing may result in strong joints with low-quality glues. Therefore, mechanical tests afford only a means of determining the strength of glued joints and may mislead a purchaser into accepting from a number of glues one of lower quality.

TESTS FOR LIQUID GLUES

Tests for judging the quality of liquid glues are not so well known as are those for animal glues. Some of the properties of liquid glues which have been described[41] as important are the following: Viscosity, jelly point, moisture content, rate of setting, hygroscopicity, chloride content, acidity and alkalinity, and keeping qualities.

The viscosity, jelly point, moisture content, acidity or alkalinity, and keeping qualitites are determined in a manner similar to those described for testing animal glues. A determination of chlorine content in the form of chlorides requires the services of a chemist. The rate of drying and the hygroscopicity may be determined by exposing a film of the glue to certain fixed atmospheric conditions (*51*).

Wood-joint tests are of more significance and value for liquid glues than for animal glues. The extremely wide variation among the different brands and grades of liquid glue make it possible to eliminate by wood-joint tests those which are the least desirable for wood joints. Furthermore, liquid glue is sold in prepared form, which reduces the chances of error in making wood-joint tests. However, very careful control of gluing conditions and of the technic of making the wood-joint test is required to obtain an accurate comparison of liquid glues.

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[40] Bogue (*6*) describes this condition as follows: "The whole mass will crumble to small cubical and rectangular fragments ranging usually from a thirty-second to an eighth of an inch on a side. Such a glue is spoken of as crazed, and since it is the farthest removed from the elastic and pliable forms it is naturally given the lowest rating by the 'inspection test.'"

[41] Tressler (*6, 51*) has described tests for liquid glues and the properties important for joining work. He finds that "fish glue of the ordinary viscosity contains from 50 to 55 per cent of glue and weighs from 9½ to 10 pounds to the gallon"; that the best fish glues have a jelly point of about 45.5° F., and "should not contain more than 0.02 per cent of chlorine as chlorides"; and that the proper reaction is "neutral to litmus and very slightly acid to phenolphthalein." To determine keeping qualities, he suggests storage at 99° for a month, and, for a determination of the rate of drying and hygroscopicity, an exposure of a film to constant atmospheric conditions.

TESTS FOR BLOOD-ALBUMIN, CASEIN, VEGETABLE-PROTEIN, AND STARCH GLUES

There are at present no generally accepted physical and chemical tests for blood-albumin, casein, vegetable-protein, or starch glues. The technic of testing these glues is less refined and perfected than for animal glues. The joint-making strength of all of these adhesives and the water resistance of blood-albumin, casein, and vegetable-protein glues are the properties most often tested. Unfortunately, joint tests are the only methods yet available for determining the suitableness of these glues.

WOOD-JOINT TESTS

A number of methods and specimens have been used for measuring the strength of glues by testing glued-wood joints. The joints for wood tests are made in various ways, for example, some end to end (fig. 18, I, J. and O), others side to side with the grain approximately parallel (fig. 18, A, B, C, D, E, G, H, K, L, M, and P), and still others side to side with the grain at right angles. (Fig. 18, F and N.) Joints are tested generally in tension or shear; however, the exact type of test varies with reference to the character of the work to be expected of the glued joint and with reference to the testing apparatus available. The "Spandau" test used in Germany and the British aeronautical-inspection test used in Great Britain are perhaps the best-known European tests. The Spandau test (*43*) is made by gluing the end grain of the two pieces together and breaking the specimen chiefly by bending. (Fig. 18, O.) The British aeronautical-inspection test (*42*) is a tension test on a joint made between a portion of two relatively thin pieces of wood with the grain parallel. (Fig. 18, H.) The British and the German tests are both regarded as rather unsatisfactory for testing the quality of a glue (*24*, *43*).

FOREST PRODUCTS LABORATORY JOINT TESTS

Two wood-joint tests have been used extensively at the Forest Products Laboratory; namely, the block-shear test and the plywood-shear test. These were adopted after experimentation with numerous methods and specimens. The block-shear test is made on lumber stock, usually about 1 inch thick, and the plywood-shear test on veneer glued into 3-ply panels. (Fig. 18, A and F.) In both tests side-grain faces are glued together; in the block-shear test the grain is approximately parallel, and in the plywood-shear test it is at right angles in adjacent plies. In the block-shear test the joint is subjected to a compressive shearing force (pl. 12), and in the plywood-shear test to a tensil shearing force. (Pl. 13.) These tests are quick, simple, and moderately accurate.

BLOCK-SHEAR TEST[42]

Two pieces of selected wood, usually hard maple, although other high-strength woods may be used, each about 1 by 2½ by 12 inches in size, are glued together face to face. The exact dimensions of the pieces may be varied somewhat without seriously affecting the test.

Care is taken to make sure that the surfaces to be joined are smooth and true and that the pieces are uniform in thickness. Extreme precautions are also taken to properly control the many other factors in gluing (p. 32). After the glued joints have aged sufficiently—for example, a week or longer—they are cut into shear specimens. (Pl. 12, A.) These specimens are placed in a testing machine which is equipped with a special shearing tool (pl. 12, B) and tested to destruction. The pressure required to produce failure is noted and the percentage of area of the joint where the wood surface is torn out by the glue is estimated. Both of these values are then used in considering the quality of the joint.

Failure of such a wood joint may occur entirely in the glue line, entirely in the wood, or partly in each. Unless the wood is of good quality, such as particularly high in density, dry, and free of defects, the failure usually occurs wholly or partly in the wood with the use of glues of medium quality or better. Inferior glues show little or no tearing of the wood.

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[42] The test specimens and the shearing tool here described and used with glued joints are distinctly different from the standard specimen and tool used in previously published reports on solid wood.

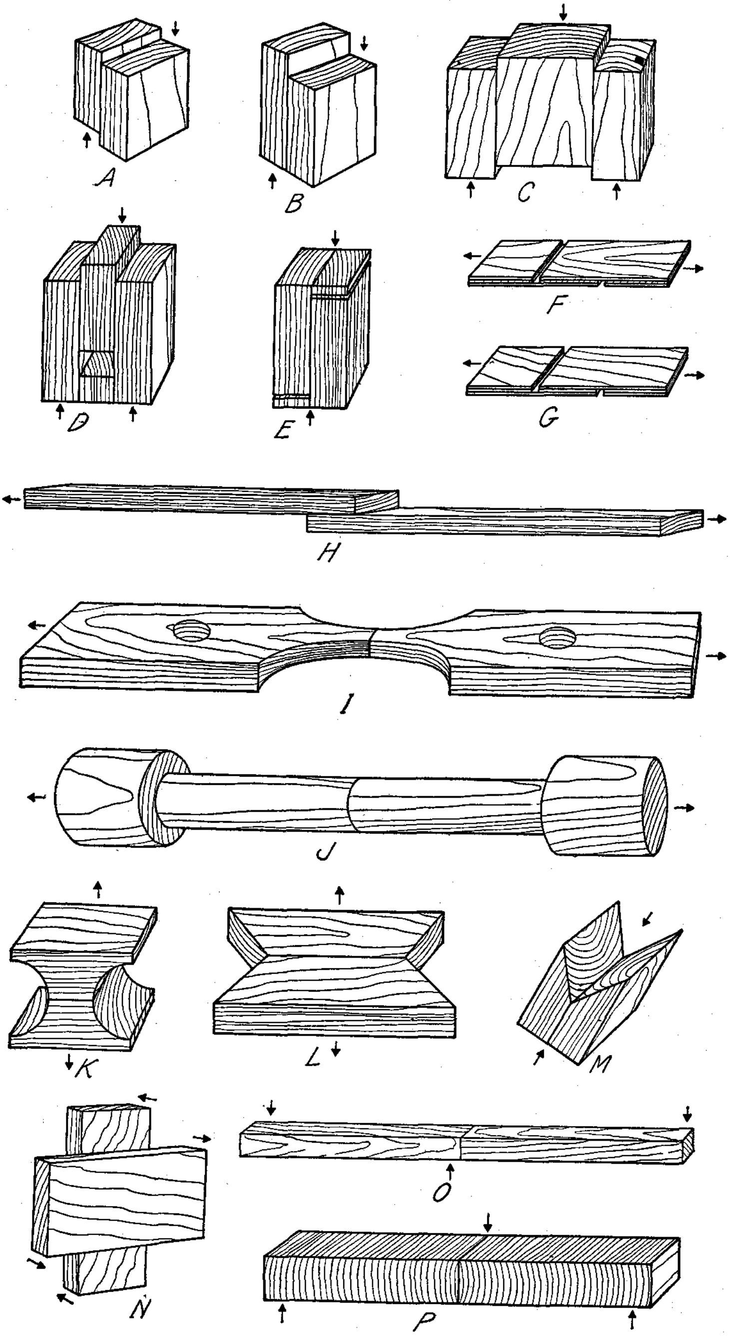

FIGURE 18.—Various types of wood-joint test specimens

The results of long use have shown the limitations of this block-shear test. It is necessary, in order to get the most uniform and the most reliable results, to standardize the gluing operation so as to avoid the effect of variable factors as much as possible and to include all practical gluing conditions. Kind, quality, density, and moisture content of the wood, care used in preparing the wood for the joints, technic used in applying the glue and pressing, and accuracy with which the specimens are cut and tested all have a bearing on the results. This test if properly conducted, however, will show whether or not the glue is capable of making a joint as strong as the wood. It will not show how much surplus strength the glue may have and therefore it will not permit a close comparison of several glues which are all capable of making joints as strong or stronger than the wood.

The block-shear test is very useful only as a measure of the success of the gluing operation, and as such it has been extensively used at the Forest Products Laboratory in studies on the effect of assembly time, pressure, amount of glue spread, and other factors which affect the strength of the joint. It is also a good test of the strength of the joint in samples of commercially glued wood, since test specimens can be cut from glued blocks of almost any shape as long as they are of sufficient size and have laminations thick enough. Furthermore, the appearance of the glued joint after the specimen is broken often enables the observer to determine whether proper conditions were used in the gluing operation.

PLYWOOD-SHEAR TEST

The plywood-shear test is usually made on glues used for veneer work. The regular test at the Forest Products Laboratory is made on three plies of birch, each one-sixteenth of an inch thick, glued with the grain of the core at right angles to the faces. The plywood is seasoned after it is glued, under uniform atmospheric conditions, and then cut into specimens of the standard form shown in Plate 13. The specimens are tested in a cement-briquette testing machine which is provided with special grips, shown also in Plate 13.[43] The specimen is subjected to tension and the failure is principally in shear although some other stresses may occur owing to the slight bending of the specimen. The breaking load and the character of failure are recorded. The specimen is easily prepared and quickly tested. The shape and construction of the specimen make it impossible to develop loads as high as those obtained in the shear-block test, but under proper control this test gives comparable results. For direct comparison of glues it is important that the plywood be of uniform construction as to species and ply thickness and that the specimens be prepared and tested in an identical manner.

Where the plies are thinner than one-sixteenth of an inch the joint failure often occurs in this test by the specimen breaking across one of the faces. In such a specimen the strength of the joint can be tested more accurately by reducing the shearing area of the test specimen without lessening the width of the specimen; that is, by making the saw cuts across the faces one-half of an inch apart instead of 1 inch. Specimens with thin faces made in this way give unit-strength values somewhat higher than where the 1 square inch testing area is used. When the plies are one-sixteenth of an inch and thicker the specimen with 1 square inch of shearing area is used. When possible, however, tests on glues are confined to the same wood, ply thicknesses, and form of specimen.

WATER RESISTANCE

The plywood-shear test may be made on either dry or wet specimens or on both. The wet test is used to measure the water resistance of glues. Specimens are soaked in water at room temperature for 48 hours and then tested while wet. Glues of low-water resistance fail in the soaking vat. Highly water-resistant glues when tested wet may show from 50 to 75 per cent of their dry strength. The Army and Navy have adopted specifications for water-resistant plywood based on the plywood-strength test. In the specifications in force in 1926 two grades were provided for by the Navy, known as grades A and B. For grade A strengths of 300 pounds per square inch tested dry and 180 pounds tested wet were required. The requirements for grade B were 225 and

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[43] Other types of machines, involving the same general method of test, have been developed and used to some extent in testing plywood joint strength.

100 pounds, respectively. Army specifications (1926) were the same as for grade B Navy plywood. In 1927 the Navy adopted a new specification requiring but one grade of plywood with a dry strength of at least 265 pounds per square inch and a wet strength of at least 145 pounds per square inch. Some allowances are made for thickness of plywood and percentage of wood failure obtained in test.[44] Only the most water-resistant glues will make plywood which passes the grade A wet-strength requirement.

The plywood-shear test, like all joint tests, must be carefully made to be of value. A standard procedure must be adopted which insures correct use of the glue, a control of the factors in gluing, and uniform procedure in testing. When made in this way it will, within limits, give results which enable a comparison of glues. Like the block-shear test, it is also valuable as a means of judging whether the glue is being used to the best advantage. It, therefore, has been used extensively at the Forest Products Laboratory for this purpose.

TESTS ON RAW MATERIALS

Blood-albumin and some casein and vegetable glues are made by combining the separate raw materials at the time of their mixing with water. In these cases it is possible to make tests on the quality of the dried albumin, the casein, and the starch to be used.

BLOOD ALBUMIN

Dry blood albumin is seldom bought under a definite specification. A 90 per cent soluble albumin is satisfactory for blood-albumin glue and can be readily supplied in this form by the manufacturer. The albumin should be comparatively free from entrained air to avoid a foamy or frothy glue. Color is not important, and the cheap dark albumin is as satisfactory as the light-colored albumin. Fat not in excess of 1 per cent, ash not more than 10 per cent, and a moisture content of about 8 per cent are known to be satisfactory limits for these factors. However, with even these requirements the albumin must be mixed into glue, and joints made and tested before there is positive assurance that it is of proper quality.

CASEIN

Commercial casein is not a uniform product (*48*), and, therefore, trouble may be caused in making glue unless the formulas are altered to suit such variations. In connection with its early studies of casein glues the Forest Products Laboratory made a series of analyses (*10*) on a large number of caseins manufactured by different methods. Each casein was mixed into glue in accordance with three different formulas. The analyses included tests for acidity, ash, fat, moisture, and nitrogen content. From this work it was concluded that any casein of reasonably good quality would make a satisfactory glue, provided changes are made in the proportions of the ingredients to suit the particular requirements of the casein.

Of the characteristics of the casein studied, the ash content seems to be most closely related to the behavior of the casein in glue making (*15*). Caseins with high ash content require larger amounts of water for use in glue making than caseins with low amounts of ash. When caseins of different ash content are used in the same formula (laboratory formula No. 4B), the variation required in the ratio of weight of total water to casein was from slightly over 2 to a little more than 3.5 for caseins ranging from grain curd to rennet, respectively (*15*). The acidity, fat, moisture, and nitrogen content did not have as important an effect on the glue-making properties of the casein as the ash content. The analytical methods so far developed do not tell with certainty what modifications, other than those which give the correct water proportions, are necessary in a given glue formula to get the best results with a particular sample of casein.

Caseins which meet the following requirements are considered satisfactory for glue-making purposes:

Color.—White or very pale cream.

Odor.—Sweet or only very faintly sour.

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[44] For more detail, see U. S. Navy, Bureau of Aeronautics Specifications Nos. 49P1a and 49P1b and U. S. Army Air Service Specification No. 82–6.

Fineness.—Ground to pass a 20-mesh screen if mixed wet or a 50-mesh screen when mixed dry with other materials.

Moisture.—Not more than 10 per cent.

Fat.—Not more than 1 per cent.

Ash.—Not more than 3 per cent for natural sour, 4.5 per cent for acid, or 8.5 per cent for rennet caseins.

Nitrogen.—Not less than 14.25 per cent.

Acidity.—Not more than 10.5 cubic centimeters of N/10 sodium hydroxide per gram.

VEGETABLE PROTEIN AND STARCH

In general, it is not practicable for the user of glue to test vegetable proteins and starch for their quality and fitness for glue making. There is comparatively little information about the essential qualities of these materials and the testing of them for glue-making purposes. Vegetable-protein glues[45] are new in the woodworking industry, and, while the class of materials from which they are made has been investigated (*27*) for some time, the available information about them is mostly of a general character. Likewise researches on starch have been carried on by a number of investigators,[46] but, in spite of the rather large amount of investigative work done, there is not yet agreement on such fundamentals as the nature of the starch grain (*46*) and how it changes into glue (*2*). Such information on these materials as is known and applied in glue making is in large part a result of private development.

So far as the present knowledge of the subject goes the tests on starch of most significance are a determination of its kind (*39*), its consistency in solution, and its adhesive property or ability to make joints. Different starches may be identified by such characteristics as size and form of granules, color reactions, appearance under polarized light, and refractive index. A consistency test at a given starch-water ratio may also give useful information but the user of glue must, for the most part, unfortunately rely upon joint tests in determining the quality of both starch and vegetable proteins for glue making.

CALCULATION OF PRESSURE ON JOINTS

SCREW CLAMPS

Where it is possible to measure the force exerted on a screw the load applied to the glue joint can be roughly calculated from the following formula, which holds only for screws with square or approximately square (acme) threads.

$$W=\frac{FL}{\left(\frac{f\pi Dm+K}{\pi Dm-fK}\right)Rm}$$

Where—

W=load in pounds.

F=force applied to lever arm in pounds.

L=length of lever arm in inches.

Dm=the sum of the diameter inside the threads plus the diameter outside the threads divided by two.

Rm=Dm divided by two.

K=pitch of screw (one divided by number of turns per inch) for single screw or lead for multiple thread screws.

f=coefficient of friction (computed to be about 0.20).

π=3.1416.

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[45] Soy bean, peanut, or cottonseed meals are generally used as bases for these glues and are described in the following patents: JOHNSON, O. ADHESIVE. (U. S. PATENT NO. 1460757.) U. S. Patent Office, Off. Gaz. 312: 132. 1923. (Re. 16,422.) U. S. Patent, Office, Off. Gaz. 350: 289. 1926. OSGOOD, G. H. GLUE. (U. S. PATENT NOS. 1601506 AND 1601507.) U. S. Patent Office, Off. Gaz. 350: 861. 1926.

[46] A bibliography on vegetable (starch) glue is given in the following: BROUSE, D. VEGETABLE GLUE. U. S. Forest Products Lab. [Pub.] 30. [Mimeographed.]

If, for example, a force of 170 pounds is exerted on an 18-inch lever arm applied to a single square thread screw, $1\frac{5}{16}$ inches in mean diameter and with a pitch of one-third (three turns to the inch) the approximate load (W) would be—

$$W=\frac{170\times 18}{\left(\frac{[0.20\times 3.1416\times 1.3125]+0.3333}{[3.1416\times 1.3125]-[0.20\times 0.3333]}\right)0.6562}$$

$$=16{,}335 \text{ pounds}=\text{total load applied by screw.}$$

HYDRAULIC PRESSES

The formula for the calculation of the amount of pressure per square inch of glue joint in a hydraulic press is as follows:

$$P=\frac{G\times A}{J}$$

Where—

P=pressure on glue joint in pounds per square inch.
G=pressure-gauge reading in pounds.
A=area of piston or ram in square inches.
J=area of glue joint in square inches.

If, for example, the gauge reading G is 2,200 pounds, the area of the piston A is 78.54 square inches (assuming the diameter of the piston to be 10 inches—the piston area is 3.1416 by 5 by 5); and the area of the panel J (assumed to be 24 by 48 inches in size) is 1,152 square inches, then the pressure per square inch of panel P would be:

$$P=\frac{2200\times 78.54}{1152}$$

or about 150 pounds.

If a given pressure per square inch of panel is desired, the necessary gauge reading G can be calculated by the following formula:

$$G=\frac{P\times J}{A},$$

the same values being used as in the case cited above,

$$G=\frac{150\times 1152}{78.54}$$

or approximately 2,200 pounds.

In the use of these formulas, it is an excellent plan to calculate the gauge reading required for different pressures and for panels of different size and to prepare the results in tables for the use of the press operator.

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