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FOREST PRODUCTS LABORATORY

In cooperation with the University of Wisconsin

MADISON, WISCONSIN

NATURE OF ADHESION BETWEEN GLUE AND WOOD

A Criticism of the Hypothesis that the Strength of Glued Wood Joints is Due Chiefly to Mechanical Adhesion

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Published in
INDUSTRIAL & ENGINEERING CHEMISTRY
January 1929

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The common woodworking glues adhere to wood in part by mechanically anchoring in the cavities of the wood. Glues may adhere specifically as well; that is, they may cling to the wood independent of any mechanical grip upon the wood structure. Evidence obtained principally from microscopical examination of the glue lines of strong and weak wood joints and from the study of the gluing characteristics of different woods has been advanced to show that specific adhesion is essential for satisfactory wood gluing. A hypothesis, based upon a comparison of the strength of wood joints in shear and tension with the strength of films of "strong" and "weak" glues in tension, has also been advanced by other investigators to indicate that glued wood joints depend for their strength chiefly upon mechanical adhesion.

This paper presents data showing that much stronger wood joints can be made with both "strong" and "weak" glues than were thought representative by the advocates of mechanical adhesion hypothesis, provided that the joints are made by the gluing procedure used by the adherents of the specific-adhesion theory. The theory that specific adhesion is essential for satisfactory wood-gluing is confirmed.

The assumption has prevailed for a long time that glue sticks to wood because it gains access while fluid to the cavities in the wood structure and then solidifies, the strength of the joint being due to the resultant intertwining of the two strong solids. Apparently the theory escaped critical examination until recently, even though it has been largely responsible for much poor gluing in the woodworking industries and for many wrong conclusions drawn by technologists from data involving tests of the strength of wood joints. For the premise leads logically to the "heat, hurry, and squeeze" method of using animal glue, in accordance with which the glue is applied hot to warm wood in a warm room, and the joint assembled and placed under substantial pressure as quickly as possible. Splendid penetration and interlocking of glue and wood are thereby secured -- together with weak joints. During a decade of study of gluing practice in the woodworking industries the starved joint,[1] produced as just described, has been found to be the most common type of unsatisfactory wood joint made with animal glue. It seems reasonable to suppose that in the past practice has been seriously influenced by inadequate theory and that the establishment of sound theory for the adhesion between glue and wood will exert a desirable influence on gluing practice.

Mechanical and Specific Adhesion Theories

In recent years notable contributions have been made to the understanding of the nature of adhesion by describing clearly and naming two distinct kinds of adhesion and by ingeniously studying joints between surfaces of different "smooth" and "porous" materials made with a variety of adhesives, as well as inventing technic for measuring the strength in tension of films of the adhesives themselves. However, since some of these contributions have been interpreted as giving support to a theory that is hostile to good wood-gluing practice, it seems desirable to examine such evidence critically. Such an examination discloses that the wood joints assumed representative were probably typical starved joints, for when similar joints are made under more favorable gluing conditions much higher strengths are obtained and characteristics are observed that the upholders of the mechanical hypothesis attribute to joints depending upon specific adhesion.

One advocate of the mechanical-adhesion hypothesis concluded that:

> Adhesive joints may be placed into two categories, namely, the specific type of true adhesion and the mechanical type of mere embedding. In some joints with porous materials both factors may be operative.[2]
>
> Strong joints may be made without adhesiveness and it will be shown that glued wooden joints appear to belong to this purely mechanical class.[2]
>
> The most important and rather surprising example of a purely mechanical joint is wood joined with gelatine or glue, where apparently even adsorption does not take place.[3]

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[1]Truax, Browne, and Brouse, Ind. Eng. Chem., 21, 74 (1929).

[2]McBain and Hopkins, Second Report of (British) Adhesives Research Committee, London, 1926.

[3]McBain and Hopkins, J. Phys. Chem., 29, 188 (1925).

The second class of joints has a purely mechanical explanation in that the adhesive is embedded in the pores and surface irregularities of the materials joined. Here the film of adhesive acts as a solidified casting holding the materials together. Glued wooden joints appear to be a conspicuous example of this class.[4]

On the other hand, advocates of the specific-adhesion theory[5] pointed out that specific adhesion between glue and wood is a necessary prerequisite of mechanical adhesion, at least with glues that contain large amounts of a volatile solvent whose evaporation causes the glue to shrink. Such shrinkage of the glue jelly on drying would loosen the "solidified casting holding the materials together" were specific adhesion lacking. They presented photomicrographs of sections through glued wood joints proving that the common woodworking glues cling firmly during drying to the walls of those cavities of wood cells into which the glue penetrates while fluid; shrinkage of the glue jelly takes place by the menisci at glue-air interfaces in wood cavities into which the glue penetrates, changing from convex to deeply concave, and by a decrease in the thickness of the glue layer, drawing the joined surfaces closer together. They showed further that studies of the technic of making strong joints with different woods and glues and of the penetration of glue into the wood cavities reveal facts difficult to reconcile with the theory that the adhesion has "a purely mechanical explanation."

This evidence of specific adhesion was set aside by the believers in mechanical adhesion with the statement that such evidence

> "overlooked the fact that the interstices and mechanical embedding to which we have referred are on an ultra-microscopic scale and therefore (not) subject to direct microscopic test; for example, we stated that gelatine passes freely through smooth continuous sheets of viscose."[6]

It was not unreasonable for the specific-adhesion advocates to assume that "pores and surface irregularities" of walnut meant the vessels that give walnut its characteristic appearance and the smaller cavities of the wood fibers easily revealed by the microscope. If mechanical adhesion is defined in terms of ultra-microscopic interstices, the conception cannot be very useful until it is first proved that the walls of the wood elements are porous in a supermolecular and submicroscopic sense and that the metals taken as typical of "smooth" surfaces are not. Though gelatine may pass freely through viscose, it has been shown[7] that the walls of the wood

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[4] McBain and Hopkins, J. Phys. Chem., 30, 114 (1926).

[5] Browne and Truax, Colloid Symposium Monograph, vol. IV, p. 258 (1926).

[6] McBain and Lee, Ind. Eng. Chem., 19, 1005 (1927).

[7] Truax and Gerry, Furniture Manfr. Artisan, April 1922.

elements are imprevious to woodworking glues even though water-soluble alkalies present in some of them apparently pass through the wood substance fairly easily and may stain the wood far beyond the limits to which the glue itself penetrates.[4,8] It may be doubted that the surfaces of wood cell walls afford an opportunity for an ultra-microscopic mechanical embedding of glues toward which they act as semipermeable membranes. For these reasons it will be necessary, for the present at least, to classify the surfaces studied as "smooth" or "porous" according to the ordinary sense perceptions of those qualities.

In a later paper the same advocates changed the adverb qualifying mechanical adhesion for wood joints from "purely" to "mainly":

> "This mechanical joining must always occur with porous bodies whether specific adhesion is present or entirely lacking. They (the mechanical advocates) found that gelatine is not adsorbed by wood from aqueous solution, and concluded that glued wood joints are mainly of the mechanical type. However, they explicitly stated that many joints will be the resultant of both factors, mechanical and specific. Indeed it may now be taken for granted that at least a small amount of specific action occurs in every case where the adhesive wets the surface."[9]

The experiment just described on the adsorption of gelatine by wood may be interpreted[5] as indicating that wood probably does adsorb gelatine. In the experiment adsorption must have occurred if the wood took up more than 24 percent of water as hygroscopic moisture. The investigators did not think it would absorb so much, because they found that filter paper takes up only 10 percent from saturated air. However, wood comes to equilibrium at 24 percent moisture content when the relative humidity is only about 90 percent at 70° F. (21° C.) and the fiber-saturation point is considerably above 24 percent.

The hypothesis of the predominance of mechanical adhesion over specific for wood joints is based upon comparisons of the strength of wood joints with the strength of films of the adhesives tested separately. Starting originally with the idea that

> "for both classes of joint the tensile strength of the film itself imposes an upper limit on the strength of joint obtainable, since the film in both cases must transmit the strain,"[4]

supporters of the mechanical hypothesis found subsequently that

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[8] Browne, Veneers, April and May, 1928.

[9] McBain and Lee, J. Soc. Chem. Ind., 46, 321 (1927); see also J. Phys. Chem., 32, 1178 (1928).

"there is no general relation between the strength of joints involving smooth surfaces and the tensile strength of various adhesives such as glue and sodium silicate. For example, gelatine may be 20 times stronger than sodium silicate, but the latter may give as strong a joint with smooth surfaces of metal. On the other hand, for any single adhesive the strength of film does appear to be parallel with the strength of the specific joint resulting."[9]

But they still hold that, for mechanical adhesion,

"with a given porous material there should be a distinct agreement between joint strength and the strength of the film of adhesive itself provided always that the adhesive is not stronger than the porous body."[9]

Nevertheless, after reviewing their own data, they write:

"Qualitatively all the results * * * agree with the mechanical explanation of joints between porous materials. It must be admitted, however, that * * * it is not so easy to obtain a decisive disproof of the specific explanation as contrasted with the mechanical explanation for a given case. At first sight it would appear that a mechanical joint should always be weaker than the adhesive in contrast to the specific type of joint. * * * Actually, however, our experiments have shown that thin films between surfaces are much stronger than the same adhesive in bulk, and this must therefore be a possibility even with porous joints. Indeed, the data * * * for sodium silicates show that the adhesive may be distinctly weaker than the wooden joints made from it.

"The most conclusive argument in favor of the mechanical explanation as distinguished from specific adhesion for glued wooden joints is obtained by comparing such widely different adhesives as sodium silicate with gelatine glue. As was pointed out, there is no relation between tensile strength of these unrelated adhesives and the strength of the specific joints which they give between smooth surfaces. On the other hand, with wood the sodium silicates give joints which are as strong as those given by gelatine glue which has been weakened to the same tensile strength. This seems a clear indication in favor of the mechanical explanation as the chief factor in the formation of glued wooden joints."

The evidence offered in support of these conclusions may be summarized as follows:

Glue	Strength		
	Glue film in tension	Walnut wood joints in side-grain gluing tested in --	
		Shear	Tension
	Lbs.per sq.in.*	Lbs.per sq.in.	Lbs.per sq.in.
Animal glue, high grade...	12,000	1,500	825
Glue mixed with an equal part of dextrose........	Less than 1,000	600	420
Sodium silicate...........	600	700	---

*14.22 lbs. per sq. in. = 1 kg. per sq. cm.

Experimental

Since the joint strengths indicated for "good" walnut joints made with animal glue are lower than joint strengths obtained at the Forest Products Laboratory, it seemed desirable to determine whether the low values can be due to the nature of the test specimen employed or whether they must be attributed to poor gluing technic. If poor gluing technic is responsible, a repetition of the joint tests with the "weak" glues under more suitable gluing conditions might give very different results. Such tests show that both sodium silicate and glue-dextrose mixtures are capable of joining wood surfaces so strongly that the failure takes place very largely in the wood when the joints are torn apart either in tension or in shear.

Glue Used

The animal glue used in the Forest Products Laboratory experiments was of a moderately high grade for a woodworking glue (viscosity 108 millipoises, jelly strength 303 grams by the standard methods of the National Association of Glue Manufacturers[10]). The film strength of its mixture with an equal weight of pure dextrose was found to be 1950 pounds per square inch when in equilibrium with air of 65 percent relative humidity at 80° F. (27° C.). Since this value is higher than that reported by the mechanical advocates, a mixture of 1 part of glue with 1.5 parts of dextrose was also

[10]Ind. Eng. Chem., 16, 310 (1924).

prepared. It had a film strength of 1100 pounds per square inch. The sodium silicate had a density of 1.415 grams per cubic centimeter and a SiO_2-Na_2O ratio of 3.25. At 30 percent relative humidity and 80° F. (27° C.) the film strength was found to be 1900 pounds per square inch, several times the value reported by the upholders of mechanical-adhesion hypothesis.

One advocate of the mechanical hypothesis states that the strength of a film of glue may be seriously influenced by the nature and amount of "lubricant" used on the ferrotype plate on which the glue film is cast. The differences in the figures given here and those reported may be due to this cause.

Manner of Making Joints

Joints for tests in shear were made with black walnut, Juglans nigra, and for test in tension with black walnut and the following woods, which are comparatively strong in tension at right angles to the grain: red gum, Liquidambar styraciflua; white ash (commercial), Fraxinus sp.; beech, Fagus grandifolia; pecan, hickory, Hicoria pecan; yellow birch, Betula lutea; persimmon, Diospyros virginiana. The lumber was seasoned by storage for many months in a room kept at 30 percent relative humidity and 80° F. (27° C.).

For the tests in shear three pieces of wood, each approximately 7/8 by 2-1/2 by 12 inches, were glued together to make a block 2-5/8 by 2-1/2 by 12 inches containing two "glue lines" designated "glue line A" and "glue line B." Nine of these blocks were prepared with each kind of glue and, after reconditioning, they were cut into test specimens as indicated in Figure 1. One test specimen from each block was of the form used by the mechanical adhesion advocates[2] and known as the R. A. E. (Royal Aircraft Establishment) compression-shear specimen. A second specimen from each block was patterned after a type of specimen used by the Forest Products Laboratory several years ago;[11] it was inserted in the shearing tool[1] in such a way as to tear off first the outside piece held in place by glue line A and then turned about to tear off the piece held by glue line B. Two remaining specimens from each block were essentially similar in form to the present standard specimen of the Forest Products Laboratory, permitting the operator to test first glue line B and then glue line A.

The joints for tests in tension were made by edge gluing two pieces 7/8 by 1-7/8 by 6 inches and then cutting them into test specimens as indicated in Figure 2. From each joint were obtained six test specimens 1/4 by 7/8 by 3-1/4 inches and nine specimens 1/8 by 7/8 by 3-1/4 inches. These specimens were broken in tension in a cement tester fitted with special jaws.[12]

[11] Allen and Truax, National Advisory Committee for Aeronautics, Report 66, (1920); see also Bogue, "Chemistry and Technology of Gelatine and Glue," p. 530, New York, 1922.

[12] Browne and Hrubesky, Ind. Eng. Chem., 19, 215 (1927).

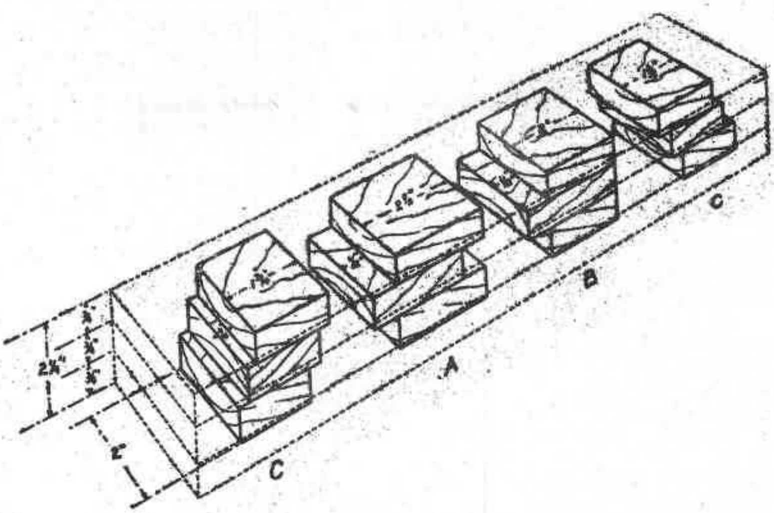

Figure 1—Method of Cutting a Glued Block into Three Types of Specimen for Test in Shear

Specimen *A* is the R. A. E. type, *B* the old type F. P. L. specimen, and the two specimens *C* the new type F. P. L. specimen

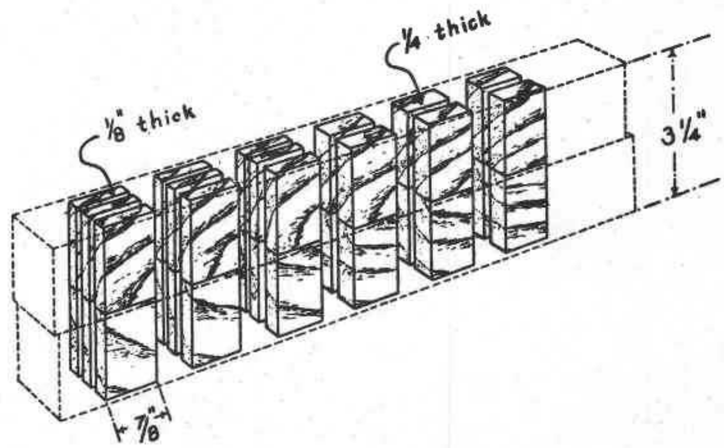

Figure 2—Method of Cutting a Glued Block into Specimens for Test in Tension

Nine specimens 1/8-inch thick and six specimens 1/4-inch thick were obtained from each block

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Gluing Procedure

The gluing was done in a room at about 80° F. (27° C.) and the wood was at the same temperature. The surfaces to be joined were smoothed on a jointer just before gluing. The animal glue, whether with or without added dextrose, was prepared with 2-1/4 parts by weight of water to 1 part of dry animal glue. The glue, after soaking in the cold water for about an hour, was melted in a thermostatically controlled glue pot at 140° F. (60° C.). The glue was applied within an hour after melting. Sodium silicate was applied at room temperature and without any addition of water. For the blocks tested in shear, glue was applied to only one of the two surfaces joined; it was applied to both surfaces of the joints to be tested in tension. "Open assembly"[1] was used so that the consistency of the glue on the wood could be observed readily; when the layer of glue congealed sufficiently to retain the imprint of the finger the joints were assembled and placed under pressure. The pressure applied in gluing the joints for test in shear was 200 pounds per square inch. No pressure gage suitable for use with the clamps holding the joints for test in tension being available, the correct pressure was judged by the amount and nature of the "squeeze out." Joints were left under pressure overnight. Those for test in shear were seasoned for 1 week in a room at 60 percent relative humidity and at 80° F. (27° C.) before cutting the specimens and testing them, those for test in tension were seasoned for 2 days at 30 percent relative humidity and at 80° F.

Results

The results of the tests in shear are given in Table 1 and of the tests in tension in Table 2. The average joint strength found for each of the four glues is higher than the representative value given by the mechanical-adhesion advocates for good joints in walnut with high-grade animal glue and two or three times as high as their representative values for glue-dextrose and sodium silicate. For glue-dextrose and sodium silicate the minimum joint strengths are much higher than their representative values. Even with these very "weak" glues the joints withstand as much load as the wood itself can reasonably be expected to sustain, and most of the test specimens fail very largely, many of them entirely, in the wood rather than in the glue line.

Comparison of Results with Those of Previous Workers

The striking difference between the Forest Products Laboratory results and those obtained by the expounders of mechanical adhesion is undoubtedly due chiefly to fundamental differences in gluing technic. When critically examined, results of the latter indicate that the gluing conditions that they adopted produced "starved" joints.[1] They applied the glue to both surfaces to be joined and then

Table I—Tests in Shear of Walnut Joints Made with Various Kinds of Glue

Glue	R. A. E. Type Test Specimen[a]						F. P. L. Test Specimen, Old Type[b]						F. P. L. Test Specimen, New Type[c]					
	Load at failure			Wood failure			Load at failure			Wood failure			Load at failure			Wood failure		
	Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
	Lbs. per sq. in.[d]			*Per cent*			*Lbs. per sq. in.*			*Per cent*			*Lbs. per sq. in.*			*Per cent*		
Animal glue	1829	1503	1650	100	85	98	2389	1561	2050	100	25	88	3105	2008	2650	100	5	86
Glue-dextrose mixed 1: 1	1758	1402	1550	100	100	100	2380	1310	1850	100	10	73	2832	1735	2250	100	5	63
Glue-dextrose mixed 1: 1.5	2025	1495	1750	100	35	86	2180	1169	1750	100	5	65	2677	948	1800	100	0	48
Sodium silicate	1781	1206	1550	100	35	93	1998	1062	1600	100	5	55	2673	1310	1900	95	0	40

[a] There were nine R. A. E. specimens with each glue. Failure usually took place by crushing of the wood in compression parallel to the grain in the projecting central piece of the specimen. A few specimens appeared to fail by cleavage of the central piece as the two side pieces spread apart under the load. Other specimens appeared to fail in shear at or near one of the glue lines.

[b] There were nine F. P. L. specimens, old type, with each glue. Each average value is therefore based upon 18 measurements, since each specimen had two glue lines tested separately.

[c] There were 18 F. P. L. specimens, new type, with each glue. Each average value is therefore based upon 36 measurements.

[d] 14.22 lbs. per sq. in. = 1 kg. per sq. cm. The speed of the testing machine was such that the shearing blade advanced at a rate of 0.0157 inch per minute. It usually took about 3 minutes to apply a load of 10,000 pounds to a test specimen. Our rate of loading was probably slightly slower than that reported by McBain and Lee.

Table II—Tests in Tension of Side-Grain Wood Joints Made with Various Glues

Glue	Wood	Load at Failure						Wood Failure		
		1/4-in. specimen			1/8-in. specimen					
		Max.	Min.	Av.	Max.	Min.	Av.	Max.	Min.	Av.
		Lbs. per sq. in.[a]			*Lbs. per sq. in.*			*Per cent*		
Animal	Gum	1136	800	1000	1625	980	1200	100	100	100
	Walnut	1560	1120	1400	1750	1310	1600	100	30	94
	Ash	1617	1300	1550	1668	1175	1500	100	100	100
	Beech	1765	1570	1650	1666	1470	1550	100	100	100
	Hickory	1863	1617	1750	1917	1567	1750	100	100	100
	Birch	2072	1790	1900	2512	1870	2050	100	100	100
	Persimmon	2300	1910	2150	2303	1617	2050	100	100	100
	Av.			1650			1650			99
Animal-dextrose mixed 1: 1	Gum	1224	940	1050	1130	634	950	100	0	36
	Walnut	1430	1200	1300	1590	1250	1350	100	10	93
	Ash	1600	1412	1500	1715	1126	1300	100	50	83
	Beech	1643	1323	1500	2140	1658	1900	100	100	100
	Hickory	1765	1001	1550	2108	1176	1600	100	100	100
	Birch	2130	1715	2000	2108	735	1650	100	5	74
	Persimmon	1857	1528	1700	2010	1520	1850	100	10	94
	Av.			1500			1500			83
Animal-dextrose mixed 1: 1.5	Gum	1224	990	1150	1765	1030	1250	100	10	87
	Ash	1715	1225	1500	1862	1373	1500	100	0	42
	Beech	1862	930	1350	1812	1520	1600	100	20	77
	Hickory	1960	1225	1500	1900	997	1500	100	0	65
	Birch	2090	1566	1850	2110	871	1300	100	5	73
	Persimmon	1960	1250	1750	2060	882	1650	100	0	87
	Av.			1500			1450			72
Sodium silicate	Gum	1078	760	900	1568	784	1050	100	0	87
	Walnut	1050	850	950	1360	870	1100	100	5	72
	Ash	1295	965	1150	1604	963	1350	100	0	70
	Beech	1642	710	1100	1496	1070	1350	100	10	88
	Hickory	1436	683	1100	1476	963	1350	100	0	66
	Birch	1570	1030	1300	1627	859	1300	100	0	35
	Persimmon	1790	1176	1450	1912	833	1600	100	5	69
	Av.			1150			1300			70

[a] 14.22 lbs. per sq. in. = 1 kg. per sq. cm. One glued joint was made with each wood and glue from which were cut six 1/4-inch test specimens and nine 1/8-inch test specimens.

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"immediately the joint was set up it was placed in a pressure device, the total pressure applied to each joint being 28 pounds, or about 7 pounds per square inch. The joints were kept under this pressure until thoroughly dry."[2]

The glue was mixed in the proportion of 20 grams of glue to 50 cc. of water in the earlier experiments,[2] but in later work 10 and 20 percent glue solutions were applied on the theory that

"the more viscous the solution of adhesive applied, the thicker the layer and the less the penetration and the weaker the joint."[9]

Such procedure would certainly produce starved joints if commercially practicable joining pressures were used, and the results indicate that the very low pressure of 7 pounds per square inch gave starved joints even with high-grade animal glue. The Forest Products Laboratory tests indicate that the addition of dextrose retards the setting of animal glue and calls for a longer assembly period. A cold glue like sodium silicate also needs a longer assembly period. It is therefore easy to understand why the exponents of the mechanical-adhesion hypothesis found their glue-dextrose and sodium silicate joints still weaker than their joints with unadulterated glue.

Table 1 shows that, although walnut joints made with the "weak" glues are strong enough to fail very largely in the wood itself, nevertheless joint strengths are slightly higher with unadulterated animal glue than with glue-dextrose or sodium silicate. Table 2 exhibits the same tendency, but indicates further that the "weak" glues may give higher joint strengths in strong wood than "strong" glue with weaker wood.

It seemed desirable, therefore, to repeat the tests in shear with the four glues and dense sugar maple, Acer saccharum. Table 3 records the results. Again all the glues make joints that break very largely in the wood; the joint strength obtained with "weak" glue in maple is higher than that obtained with unadulterated animal glue in walnut.

Comparison of Joint Strengths with Film Strengths

In the light of the notably different results obtained at the Forest Products Laboratory, in making wood joints with the "weak" glues used by the expounders of the mechanical-adhesion hypothesis, the deductions drawn by them from comparison of joint strengths with film strengths must be re-examined. They find that the following trends are characteristic of specific adhesion between smooth surfaces:

(1) Such joints often exceed by several fold the tensile strength of the adhesive itself.[13]

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[13] McBain and Lee, J. Phys. Chem., 31, 1675 (1927).

(2) The strength of such joints is parallel to the mechanical constants of the materials joined. * * * Joint strengths rise with tensile strength and elasticity (of the materials joined).[14]

(3) There is no general relation between the strength of joints involving smooth surfaces and tensile strength of various adhesives such as glue and sodium silicate. For example, gelatine may be 20 times stronger than sodium silicate, but the latter may give as strong a joint with smooth surfaces of metal. On the other hand, for any single adhesive (such as animal glue of different grades or with added dextrose) the strength of film does appear to be parallel with the strength of the specific joint resulting.[8]

(4) The thinner the layer of adhesive, the stronger the joint. The effect of thickness is not appreciable with very thick films but is rapidly increasing when the thinnest possible films are studied.[13]

Table 3.--Tests in shear of maple joints made with various kinds of glue

Glue	Number of -- Joint	Number of -- Specimens*	Load at failure Maximum	Load at failure Minimum	Load at failure Average	Wood failure Maximum	Wood failure Minimum	Wood failure Average
			Lbs. per sq.in.**			Percent		
Animal	4	40	4810	3190	3950	100	10	55
Glue-dextrose 1:1	4	20	3802	2808	3350	100	10	70
Glue-dextrose 1:1.5	7	35	3950	2470	3150	95	5	23
Sodium silicate	4	40	4015	2290	3000	100	5	68

*New type of F. P. L. test specimen.
**14.22 lbs. per sq. in. = 1 kg. per sq. cm.

Illustration of the first and third of these trends is afforded by the wood-joint data of Tables 1, 2, and 3; the strength of wood joints is often more than twice the strength of the adhesive itself, "weak" sodium silicate has a joint strength of the same magnitude as "strong" animal glue, yet wood joints made with glue-dextrose are consistently, though very slightly, lower in strength than joints made with unadulterated animal glue. The second trend of specific adhesion, connecting joint strength with the strength of the material joined, also finds illustration in these data, but wood is so different in structure and chemical composition from the metals and crystalline compounds chosen by the investigators of mechanical adhesion to represent joints depending upon specific adhesion, that no importance

[14] McBain and Lee, Proc. Roy. Soc. (London), 113, 606 (1927).

should be attached to the agreement in this respect. The fourth trend cannot be demonstrated in wood joints, because the surface of wood is by nature rough enough to bring the thickness of the glue film into the region in which the effect of thickness is not appreciable.

When wood joints are made with the "weak" glues used by the interpreters of mechanical-adhesion hypothesis under gluing conditions favoring the production of good joints, and when the characteristics of the joints are compared with those of typical joints between "smooth" surfaces after the manner adopted by them, no differences are found that indicate a fundamental difference in the nature of the adhesion. On the contrary, there are striking similarities suggesting that the same kind of adhesion is probably operative. Nevertheless, no conclusions should be drawn about the nature of adhesion solely from evidence involving joint tests, especially when it is remembered that glue-dextrose mixtures and sodium silicate have not been studied so carefully as unadulterated animal glue and the gluing conditions under which they give best results are not so well known. The technic of testing the strength of films of glue is also in an early stage of development and the results reported so far may not be truly representative. Fortunately, considerations of a different kind, which are open to less serious criticism, have already been presented[5] to show that customary woodworking glues adhere specifically to wood surfaces. Strong wood joints could probably be made with ordinary glues if the wood presented only smooth, nonporous surfaces, but the fact that wood is porous makes it easier to glue it well, because it provides a larger area of interface between glue and wood for the action of specific adhesion and because it brings mechanical adhesion into play as well.

Mechanical adhesion to wood without concomitant specific adhesion is theoretically possible, of course, and practical examples of it can probably be found. There is reason to believe that the usual linseed-oil house paints cling to wood chiefly, if not entirely, by mechanical adhesion. The ease with which the bond between such coatings and the wood can be broken in blistering and peeling and the characteristic ultimate failure of the coatings by crumbling or flaking off the dense summerwood of the conifers while it remains clinging to the neighboring springwood suggest that the nature of the adhesion between paint and wood may be fundamentally different from the adhesion between glue and wood.

Conclusions

(1) Wood joints materially stronger than those reported by the advocates of the mechanical-adhesion hypothesis can be made with (1) animal glue, (2) animal glue containing dextrose, and (3) sodium silicate, provided that more favorable gluing procedure be chosen for making the joints.

(2) Wood joints obtained with these three glues under good gluing conditions display two striking properties that have been previously described as characteristic of specific adhesion, namely:

(a) The wood joints may be several times as strong as the glues from which they are made, (b) the strength of the glued joint is decreased, although slightly, by adulterating the glue with a material that weakens the film of the glue tested separately.

(3) Wood joints obtained with the three glues satisfy all criteria of joints depending largely upon specific adhesion with respect to which they have been examined.

(4) Wood joints made with the woodworking glues in common use depend for their strength very largely upon specific adhesion, although the porous nature of wood brings mechanical adhesion into play also.