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Comparative study on physical and mechanical properties of laminated veneer lumber and plywood panels made of wood from fast-growing *Gmelina arborea* trees

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Abstract Laminated products, such as laminated veneer lumber (LVL) or plywood (PW), have become important recently. The objective of this study was to determine and compare properties of panels fabricated with veneers of *Gmelina arborea* trees in a fast-growth plantation and glued with phenol formaldehyde resin. The results showed that LVL and PW physical and mechanical properties are comparable to those of solid wood with a specify gravity of 0.60. Moreover, these panels can be cataloged into group 2 of PS 1-95 of the Voluntary Products Standard of the United States. The difference in physical properties was not statistically significant between LVL and PW panels, except for water absorption. Some mechanical properties, such as hardness and glue-line shear, modulus of rupture in perpendicular flexure, nail and screw withdrawal parallel, and perpendicular strength, were statistically different between LVL and PW. However, no differences were established for the modulus of elasticity, tensile strength parallel to the surface, or tensile strength perpendicular to the surface. The differences were attributed to the venners' orientation in the panels studied.

Key words Veneers · Delamination · Adhesive · Resistance · Tropical wood

Introduction

Wood is an important material that can be used in different forms and situations. Its characteristics are comparable to those of other structural materials,[1] but increased demand for wood has caused a decrease in forest resources.[2] One way to increase forest resources, thereby protecting the natural forest, was developed wherein composite products from solid wood are manufactured.[2]

Veneer products, such as plywood and laminated veneers, have been developed as an alternative to solid products.[3] This method allows small logs from plantations and unimportant species to be utilized in commercial products.[4] Veneer products have various advantages over conventional solid wood, such as increased dimensional stability, uniformity and higher mechanical strength, improved stress-distributing properties, reduced processing cost, availability in larger sizes, and better appearance.[1,5]

Physical and mechanical properties of veneer products are governed by the properties of the wood species utilized, the manufacturing process, the quality control process, and finally the application of these products.[4] Plywood (PW) and laminated veneer lumber (LVL) (as wood-based material) are gaining increased interest for their benefits in structural and nonstructural usage[6]; in fact, they are starting to be used in applications typically dominated by steel and concrete.[4] In the future, with the reduced availability of large, solid sawn structural members, engineered wood products will play an even more important role as structural material. Another important advantage of these products is their biological benefits, as low energy consumption is used in their transformation, and their natural composition means that the material is biodegradable, whereas steel and concrete are not.[6]

Gmelina arborea (melina) is widely used in commercial reforestation programs in tropical countries for sawn wood production, pulp, and bioenergy.[7] *G. arborea* is one of the most important species of timber for solid wood production in Costa Rica, for example. Approximately 65 000 hectares are planted in different ecological zones of Costa Rica.[8] *G. arborea* plantations are being managed under new concepts oriented to fast growth and high productivity.[9]

However, the usage of *G. arborea* from fast-growth plantations in laminated products is limited in Costa Rica. Some studies were carried out to investigate the possibilities of the using this wood in glulam and LVL products.[10,11] However, these studies had researched the mechanical

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resistance of finger-joints made of *G. arborea* wood for manufacturing glued laminated beams[10] and the mechanical properties of LVL as flanges of a composite "I" beam.[11] Therefore, the objective of this study was to determine and compare physical and mechanical properties of plywood and five-layer LVL. A better understanding can help us develop productive uses for fast-growth plantations, thereby mitigating environmental problems with disappearing tropical natural forests.

Materials and methods

Wood materials

Three *G. arborea* panels of PW and three LVL panels were selected from the production process at Maderas Cultivadas de Costa Rica S.A in Costa Rica.[12] They were chosen randomly during 2 days of production. The panel dimensions were 244 cm long × 122 cm wide × 12 mm thick. The veneers were obtained from rotating-shift trees growing under a fast condition in a pure plantation (12–14 years).

Process

Logs >25 cm in diameter and about 2.6 m long were rotary peeled into veneers on a lathe. The average moisture content (MC) of dried veneers varied from 6% to 8%. Six-veneer panels of PW and LVL were used; veneers 3 mm thick were used for the exterior face, and veneers 1.5 mm thick were used in the central part (Fig. 1). PW and LVL panels were classified in the AA category on the Costa Rican market, where exterior veneers are the best quality (A) and central veneers are B or C quality. The layers were glued using phenol formaldehyde (PF) resin, which was applied on one face of the veneer with a glue spread rate of 220 g/m^2 using a glue roller. The panels were pressed at 150 bars at a temperature of 120°C for 7 min. The panels were conditioned for 24 h, after which they were cut into their final dimensions.

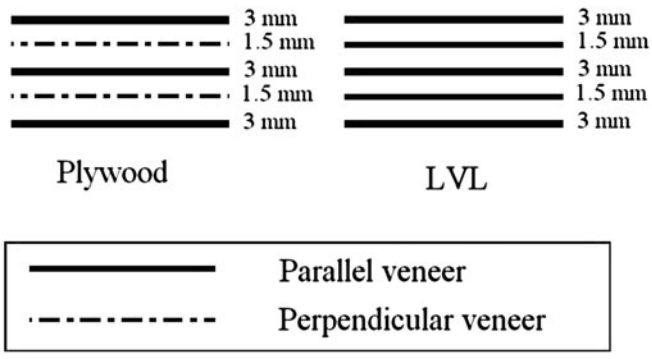

Fig. 1. Arrangement of *Gmelina arborea* veneers in plywood and laminated veneer lumber (LVL) panels

Sampling method

The amount, grain direction, and size of the test probe for physical and mechanical properties were determined for the panels, and they were sampled randomly. The sampling was carried out according to the standard EN 326-1.[13] Figure 2 shows the distribution of probes in half panels (122 × 122 cm). To complete the number of samples required for testing, the others were cut on the other half panel. The probes for specific gravity, direct MC measurement, delamination, tensile strength perpendicular to surface, glue-line shear test, and shear strength in the plane of the board are not shown in Fig. 2 because their dimensions were extremely small (5 × 5 cm), and they were obtained from the parts left over in the other half panel.

Physical, delamination, and mechanical properties determination

Specific gravity, density, direct MC measurement, variation in thickness, water absorption, and thickness swelling were determined to study the physical properties. ASTM standard D-2395[14] was used for the specific gravity determination, ASTM standard D-4442[15] for MC measurement, and

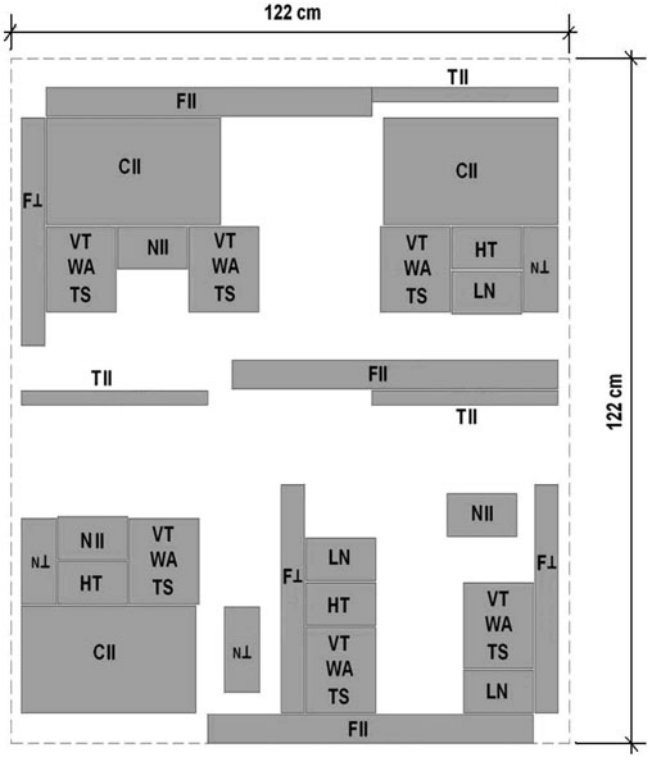

Fig. 2. Distribution of samples in laminated panel of *G. arborea* (122 × 122 cm). F||, center, point flexure test (parallel); F⊥, center, point flexure test (perpendicular); C||, compression test for large specimens (parallel); T||, tensile properties of small specimens (parallel); HT, hardness test; LN, lateral nail resistance test; N||, nail and screw withdrawal (parallel) test; N⊥, nail and screw withdrawal (perpendicular) test; VT, variation in thickness; WA, water absorption; TS, thickness swelling

Table 1. Statistical parameters of physical properties of 12 mm-thick plywood and LVL panels (244 × 122 cm) manufactured with *Gmelina arborea* wood from a fast-growth plantation

Properties	Plywood	LVL	Average	ANOVA	
				Medium square of error	F value
Specific gravity	0.52 (0.04)^{A}	0.52 (0.03)^{A}	0.52 (0.03)	0.16	NS
Density at 12% (kg/m^3)	516 (44.03)^{A}	523 (24.71)^{A}	519 (34.37)	1172	NS
Moisture content (%)	12.35 (1.64)^{A}	12.10 (1.22)^{A}	12.23 (1.44)	0.00	NS
Thickness variation (mm)	1.26 (0.91)^{A}	1.23 (0.92)^{A}	1.25 (0.92)	0.00	NS
Water absorption (%)	17.79 (2.78)^{A}	15.23 (1.10)^{B}	16.51 (1.94)	0.00	**
Thickness swelling (%)	2.09 (0.92)^{A}	1.76 (2.35)^{A}	1.93 (1.64)	0.62	NS

Results are expressed as the mean; values in parentheses represent the coefficient of variation. Different letters (superscript A, B) in plywood and LVL for the same wood properties are different statistically at 99%
LVL, laminated veneer lumber; ANOVA, analysis of variance
* Significant at 95%
** Highly significant at 99%

ASTM standard D-1037[16] for variation in thickness, water absorption, and thickness swelling. The delamination properties were measured by shear strength in the plane of the board test, and it was determined under three conditions: air-conditioning, boiling water, and vacuum-pressure. The air-conditioned test was determined according to ASTM D-1037,[16] for boiling water JAS[17] was used, and for vacuum-pressure ASTM D-2559 was followed.[18] Eleven types of mechanical test were conducted in this study: tensile strength parallel to the surface (T‖), tensile strength perpendicular to the surface (T⊥), compression strength parallel to the surface (C‖), hardness test (HT), glue-line shear test (GS), shear strength in the plane of the board (PS), center-point flexure test parallel and perpendicular to the surface (F‖ and F⊥, respectively), lateral nail resistance strength (LN), and nail and screw withdrawal parallel and perpendicular strength (N‖ and N⊥, respectively). ASTM standard D-3500[19] was use in T‖, ASTM standard D-3501[20] for C‖, ASTM standard D-3043[21] for F‖ and F⊥, and ASTM standard D-1037[16] for T⊥, GS, PS, HT, L‖, L⊥, and for nail and screw determinations.

Statistical analysis

The normality and the presence of extreme data or outliers were verified for each panel property. A general statistical description (average and coefficient of variation) was then performed for the various panel properties. An analysis of variance (ANOVA) was used to test differences between the PW and LVL panels. Mean differences between panels were evaluated using Tukey's test ($P < 0.01$).

Results and discussion

Physical properties

Average and statistical analyses of physical properties for PW and five-layer LVL of *G. arborea* are detailed in Table 1. The average values for the two panels were as follows: specific gravity 0.52; density 519 kg/m^3; MC 12.23%; thickness variation (±) 1.25 mm; water absorption after 24 h 16.51%; thickness swelling 1.93%. The ANOVA (Table 1) did not show statistical differences for physical properties, with the unique exception of water absorption, where PW had higher absorption than LVL (Table 1).

Perhaps by using the same raw material and the same manufacturing conditions for PW and LVL panel fabrication there would be no statistically significant differences in their physical properties (Table 1). However, water absorption after 24 h was different between PW and LVL panels. Several studies have confirmed scarce or null variation of physical properties in different veneer products.[2,22] Shukla and Pascal[2] showed that physical properties of LVL made with different hardwood species are mainly governed by the physical properties of the wood species, not by manufacturing conditions. The results of Abdul et al.[22] agreed with our findings. They found that thickness swelling percentage of PW made with *Betula pubescens* and *Alnus glutinosa* wood is influenced by species characteristics, such as moisture content, but that these physical properties were not affected by the size or thickness of the veneers.

Wood is a hydroscopic material.[23] The panels in our study were subjected to water absorption for 24 h. The results indicated that this physical parameter was different in PW and LVL panels (Table 1). Water absorption was lower in LVL than PW, suggesting that the LVL panels are less susceptible to dimensional change than PW panels. Although the two panels were fabricated from the same raw material, the difference found between the panels can probably be attributed to the orientation of the veneers in the panels.

The values for the physical properties obtained with *G. arborea* agreed with those of other studies. Babatunde et al.[24] found thickness swelling from 1.13% to 4.22% and from 17.81% to 18.77% due to water absorption. These values are similar to the ones reported in Table 1. Those authors mentioned that *G. arborea* had physical properties similar to those of *Leucaena leucocephela*. Species with similar density,[2,5] such as *Acer saccharinum* (542 kg/m^3), *Liriodendron tulipifera* (492 kg/m^3), and *Acacia mangium* (620 kg/m^3), have physical properties close to those of *G.*

arborea. However, an advantage of *G. arborea* over these other species is that the water absorption and thickness swelling are lower. Water absorption of *G. arborea* averaged 16.51%; whereas *A. saccharinum*, *L. tulipifera*, and *A. mangium* reported higher values: 66.75%, 44.31%, and 20.0%, respectively.[2,5] For thickness swelling, *A. saccharinum* and *L. tulipifera* reported 3.13% and 4.77%, respectively,[2] which are greater than those for *G. arborea*. However, *A. mangium* reported 1.57%,[5] a value slightly lower than that for *G. arborea*. The physical properties obtained for *G. arborea* can be compared with those of group 2 of the Voluntary Product Standard PS 1-95 for Construction and Industrial Plywood from the U.S. National Institute of Standards and Technology.[25] Specific gravity averaged 0.52 in *G. arborea*; and species in group 2 of PS 1-95 had similar values (0.35–0.55). Therefore, PW of LVL panels fabricated with *G. arborea* can be classified in group 2 of this standard.

Delamination properties

Shear strength evaluated under three conditions is shown in Fig. 3. The strength resistance varied from 1.72 to 3.97 MPa. Although LVL panels had a lower shear strength in boiling water than when the condition was air-dried or vacuum-pressed, the difference was not statistically significant. The boiling water vacuum-press test decreased the shear strength significantly compared with the air-dried test in PW panels, but no differences were established between the boiling water and the vacuum-press tests (Fig. 3). LVL panels presented higher shear strength than PW panels under all conditions (Fig. 3). This difference can be attributed to the different orientation of veneers in the panels. PW is manufactured from sheets of cross-laminated veneers, which is different from the arrangement in LVL panels, where the sheets are parallel-laminated veneers. During the shear test, the force applied to PW is perpendicular to the veneer direction, whereas the force applied to LVL panels is parallel to the veneer direction. The decreased shear resistance seen after the boiling water test or vacuum-press test in PW (Fig. 3) is produced by weakening of the glue line between two sheets during the aging test.[26]

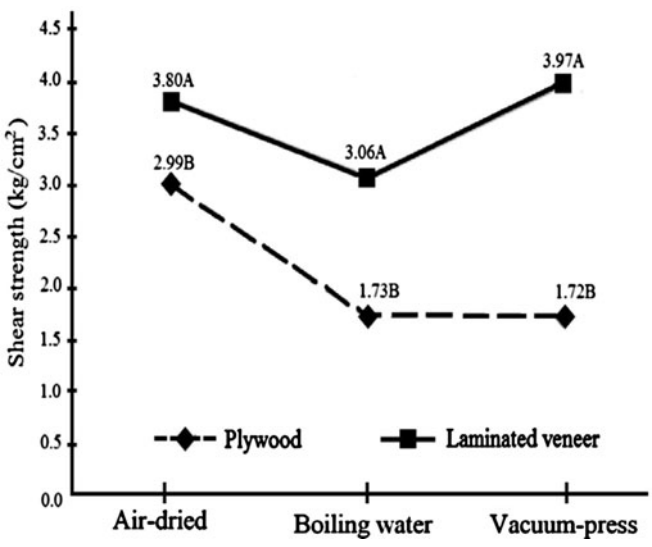

Fig. 3. Shear strength average obtained in 12 mm thick plywood and laminated veneer made of *G. arborea* wood (244 × 122 cm). Different letters (A, B) are different statistically at 99%

Vick[27] noted that sheets or veneers cut from logs with rotary peeler are characterized by the presence of small checks, called lathe checks, on the side of the veneers; no checks are present on the other side of the sheet. Lathe checks are formed when the veneer is bent sharply as it passes between the knife and the nosebar.[28] During the glue process, the nonchecked side is glued onto the checked side of the veneer; therefore, the irregularities on the surface are filled by adhesive. We think that the irregularities on the surface are increased by the perpendicular joining of two veneers in PW. This situation increases the adhesive quantity applied and therefore decreases glue-line resistance in PW. When the veneers are glued parallel in LVL panels, the irregularities decrease by adjusting the checks on the surface of veneers. Therefore, empty spaces in the sheets decrease and glue-line resistance increases. It is possible that the boiling water and vacuum-press tests have a greater effect on PW than on LVL, so the shear strength for these test conditions show lower resistance in PW (Fig. 3).

ASTM D-5751 "Adhesives for Structural Laminated Wood Products for Use Under Exterior (Wet Use) Exposure Conditions" established minimum requirements for shear strength of the glue line for structural usage.[29] These values are derived from the resistance of solid wood in the shear test. Moya[8] estimated that the shear strength of solid wood of *G. arborea* was 6.2 MPa. According to ASTM D-5751,[29] it was calculated as the minimum and the mean shear strength (Table 2). PW and LVL panels had higher shear resistance than the minimum values established by the ASTM standard under all conditions of testing. The shear strength of the PW panels did not reach the mean resistance of solid wood, whereas the shear resistance of the LVL panels had mean values above the minimum under all conditions (Fig. 1, Table 2). We observed that LVL panels are widely different with respect to resistance. On the contrary, although the shear strength of PW panels is higher than the minimum shear resistance required, its values are close to the minimum (Fig. 1, Table 2). Therefore, LVL and PW panels can be classified as satisfactory for structural uses, but special care must be taken with PW panels because they reach only the minimum shear strength of solid wood.

Mechanical properties

The averages and statistical analysis of physical properties for 12 mm thick PW and five-layer LVL of *G. arborea* are presented. It was found that PW panels have higher resistance than LVL at maximum load in terms of hardness, the glue-line test, and maximum load in lateral nail withdrawal

Table 2. Average and minimum resistance in shear strength test for plywood and LVL derived from the shear strength of solid wood (*G. arborea*)

Parameter	Resistance (MPa)			
	Solid wood	Natural test	Boiling water	Vacuum-press
Mean	6.2 (100%)	3.72 (60%)	2.48 (40%)	3.10 (50%)
Minimum	6.2 (100%)	1.86 (30%)	1.24 (20%)	1.55 (25%)

Values in parentheses represent the percentage of shear strength in solid wood established by ASTM D-5751-99

Table 3. Average and statistical parameters of the mechanical properties of 12 mm thick plywood and LVL and solid wood of *G. arborea*

Mechanical properties	Plywood	LVL	Solid wood	ANOVA	
				Medium square of error	F value
Tensile, parallel					
MOE (MPa)	45.38 (32.62)^{A}	41.37 (25.40)^{A}	–	0.00	NS
Maximum stress (MPa)	33.46 (23.46)^{A}	37.40 (16.35)^{A}	46.1	0.00	NS
Tensile, perpendicular: maximum stress (MPa)	0.66 (0.14)^{A}	0.76 (0.10)^{A}	0.47	0.15	NS
Compression parallel					
MOE (MPa)	23.05 (7.47)^{A}	20.66 (16.68)^{A}	–	138	NS
Maximum stress (MPa)	18.77 (4.85)^{A}	10.13 (6.86)^{A}	31.19	47	NS
Hardness: maximum load (kg)	223.47 (25.49)^{A}	192.96 (27.33)^{B}	285	555	**
Glue-line shear: maximum stress (MPa)	3.06 (0.79)^{A}	1.47 (0.34)^{B}	–	0.00	**
Shear in the plane: maximum stress (MPa)	3.68 (0.86)^{A}	4.41 (1.19)^{B}	6.18	10.95	*
Flexure perpendicular					
MOE (GPa)	1.73 (0.66)^{A}	2.21 (3.96)^{A}	–	821	NS
MOR (MPa)	17.68 (6.23)^{A}	12.28 (34.04)^{B}	–	0	**
Flexure parallel					
MOE (GPa)	11.21 (3.65)^{A}	12.86 (2.88)^{A}	8.14	1089	NS
MOR (MPa)	46.59 (15.14)^{A}	61.39 (15.93)^{B}	49.32	2462	**
Lateral nail withdrawal					
Maximum load (kg) at 9 mm	93.24 (18.13)^{A}	63.96 (22.70)^{B}	–	422	**
Maximum load (kg) at 19 mm	–	97.49 (21.13)	–	–	–
Screw withdrawal					
Maximum load (kg), parallel	106.06 (10.76)^{A}	90.52 (15.91)^{B}	–	69	**
Maximum load (kg), perpendicular	112.50 (11.31)^{A}	90.28 (7.01)^{B}	–	4.86	**
Nail withdrawal					
Maximum load (kg) parallel	12.95 (4.17)^{A}	14.49 (3.10)^{B}	–	5.25	**
Maximum load (kg) perpendicular	16.38 (3.44)^{A}	15.08 (3.56)^{B}	–	3.33	**

Results are the average. The values in parentheses represent the coefficient of variation. Different letters in plywood and LVL for the same wood properties are different statistically at 99%
Lateral nail withdrawal at 19 mm was not determined because the nail is less resistant than plywood
MOE, modulus of elasticity; MOR, modulus of rupture
* Significant at 95%
** Highly significant at 99%

and screw withdrawal (Table 3). On the contrary, PW has lower values than LVL in terms of shear in the plane test, modulus of rupture (MOR) in flexure-parallel, and maximum load in nail withdrawal (Table 3). No statistical differences between PW and LVL panels were established in regard to the modulus of elasticity (MOE) and maximum stress in the tensile-parallel test, maximum stress in the tensile-perpendicular test, maximum stress in the compression-parallel test, and the flexure-parallel test (Table 3).

Mechanical properties of PW and LVL panels made of *G. arborea* wood from a fast-growth plantation have resistance similar to solid wood in regard to most properties, with the exception of maximum stress in tension and compression parallel to the grain (Table 3). It is important to note that it has been suggested but not established that some mechanical properties are affected by the orientation of the veneer in the panel. The values for stress in tensile-parallel, tensile-perpendicular, compression-parallel, and MOE in flexure-perpendicular were no statistically different between panels. However, other mechanical properties were affected by the orientation of the veneer in the panel, such as hardness, two kinds of shear test, the MOR of two flexure tests, and nail and screw withdrawal.

Another important point to emphasize is that mechanical properties of glued veneer products, specifically nail and screw withdrawal, were affected by the orientation of the veneer in the panel. For example, PW panels have better resistance if two pieces are joined by nails or screws. However, when two pieces are nailed parallel to the fiber, LVL panels have better resistance.

Abdul et al.[22] noted that some mechanical panel properties depend on panel density, nail and screw diameter, deep

penetration of nail and screw, wood species, moisture content, spiral grain, adhesive characteristics, and veneer thickness. Nevertheless, the results obtained in this study confirmed that differences in many panel properties (including physical, mechanical, and delamination properties) can be attributed to the orientation of the veneer in the panel.

Conclusions

The PW and LVL panels made of *G. arborea* veneer from a fast-growth plantation had similar specify gravity, density at 12% MC, and thickness variation. There was a difference between them in regard to water absorption. The rare physical property differences between panels are due to the raw material characteristics, not veneer orientation.

The aging tests (boiling water and vacuum-press) produced negative effects in PW and LVL, but the effect on PW was greater; the shear resistance of PW was longer than that of LVL. The shear strength of both veneer products met the minimum requirements of ASTM standard D-5751 for adhesives utilized in structural panels, but PW did not reach the mean value required by the ASTM standard.

Most mechanical properties of PW and LVL composed of *G. arborea* wood are different, and these differences were attributed to the orientation of the veneer in the panels. On the other hand, the mechanical properties of these veneer products were similar to those of solid wood. The physical properties obtained for *G. arborea* can be compared to those of group 2 in the Voluntary Product Standard PS 1-95 "Construction and Industrial Plywood" from the U.S. National Institute of Standards and Technology (1996).

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