Physical and mechanical properties of three agroforestry tree species from Kerala, India

A. Shanavas and B.M. Kumar*

Department of Silviculture and Agroforestry, College of Forestry, Kerala Agricultural University, KAU PO, Thrissur 680 656, Kerala

Received 22 June 2006; received in revised form 30 August 2006; accepted 31 August 2006.

Abstract

Wood properties of three locally important fast growing tree species (*Acacia auriculiformis, Acacia mangium,* and *Grevillea robusta)* occurring as scattered and boundary planted trees on the agricultural lands of Kerala were evaluated. Species and sample positions exerted a profound influence on the physical and mechanical properties of wood. Basic wood density of *A. auriculiformis* was greater than that of *A. mangium* and *G. robusta,* while moisture content followed a reverse sequence: *G. robusta* > *A. mangium* > *A. auriculiformis.* Wood density also increased from inner to outer positions along the radial direction, except for *G. robusta*. Although moisture content decreased from the inner to outer position of the specimens for *A. mangium*, no predictable pattern was discernible in this respect for the other two species. Shrinkage along radial direction followed a trend similar to that of wood moisture content. Most strength properties, however, followed a pattern analogous to that of wood density. Attributes such as work to limit of proportionality and work to maximum load in static bending, compressive stress at limit of proportionality in parallel to grain, compressive stress at limit of proportionality in perpendicular to grain, and end-hardness of *A. auriculiformis* were also greater than the values reported for teak (*Tectona grandis*). However, the physical and mechanical properties of *A. mangium* and *G. robusta,* except shrinkage, were inferior to teak.

Keywords: *Acacia auriculiformis, Acacia mangium,* Compressive stress, *Grevillea robusta,* Modulus of elasticity, Modulus of rupture, Maximum crushing stress, Shrinkage, Wood specific gravity.

Introduction

Agroforestry is often heralded as a promising land use option with considerable potential for commercial timber production (Kumar, 2005). Coincidentally, timber species abound on farmlands – often as scattered and/or as boundary planted trees (Kumar et al., 1994). However, for a wide range of such species, little is known about the properties of timber sourced from agricultural lands (but see Bhat, 2005). Furthermore, concerns regarding the physical and mechanical properties of timber harvested from fast growing tree species have been articulated (Pandey and Brown, 2000), primarily because of the differences in strength properties of stand-grown trees (plantations) and trees from the natural forests (Shukla et al., 1999). Hence, a study was undertaken to evaluate the physical and mechanical properties of three fast growing multipurpose tree species (*Acacia auriculiformis, Acacia mangium* and *Grevillea robusta)* of local importance in Kerala. Although their suitability as a timber in the Indian context has been evaluated previously (e.g., *A. auriculiformis*: Kumar et al., 1987; Shukla et al., 1990; *A. mangium*: Scharai and Kambey, 1989; Dhamodaran and Chacko, 1999; *G. robusta*: Khanduri et al., 2000), such data from the agroforestry systems of Kerala are scarce.

Materials and Methods

Three tall, straight trees each of the focal species (diameter range: 27 to 41 cm at breast height and age 10–15 years), having no defects or disease incidence, were selected

*Author for correspondence: Phone + 91-487-370 050; Fax + 91-487-371040; E-mail <bmkumar.kau@gmail.com>.

from the agricultural lands of central Kerala. In view of the difficulty in sourcing sample trees from a particular site, trees from three locations (based on a reconnaissance survey) were selected (i.e., two of *A. auriculiformis* from Thiruvazhamkunnu and one from Vellanikkara; two of *A. mangium* from Vellanikkara and one from Thiruvazhamkunnu; and two of *G. robusta* from Peerumedu and one from Perumbavoor). The selected trees were felled at ground level in March 1998 and 1 m long billets extracted from the trunk sections 1 m above the ground. All billets were numbered and marked with 3 x 3 cm squares on the smaller end for conversion into 2.5 x 2.5 cm scantlings. The scantlings were surfaced to 2 x 2 cm cross sections to obtain small clear specimens for different tests (see below). Three specimens per tree conforming to the IS 1708 standards of BIS (1986) were selected for each test from near the pith (inner), middle, and peripheral (outer) regions.

Basic density and green moisture content

Three specimens [2 x 2 cm (cross section) and 2.5 cm long] each per species and radial position (inner, middle, and outer) were weighed in green condition and their volume (correct to 0.01 cm^3) determined by the water displacement technique. Following this, the specimens were oven-dried at 103±2°C until constant weights and then coated with a thin layer of hot paraffin wax and the volume of the paraffin-coated specimens determined. Basic density (oven-dry weight/green volume) and moisture content (green weight basis) were also computed.

Shrinkage

Wood specimens (2 x 2 cm in cross section and 5 cm long) in green state were weighed (0.001 g accuracy) and conditioned in a climatization room to achieve constant weights over a two-month period. The samples stabilised at about 12% moisture content (verified by periodical testing) were then oven-dried (103±2°C) until constant weights. Lengths of the specimens along radial or tangential plane at green, air-dry (12% moisture), and oven-dry conditions were measured (0.002 cm accuracy) and the radial and tangential shrinkages calculated.

For estimating volumetric shrinkage at green, air-dry, and oven-dry conditions, volume of the specimens (2 x 2 cm cross section and 6 cm long) weighed initially (green condition correct to 0.001 g) was determined by water displacement (correct to 0.01 cm^3). After taking out from water and wiping with a dry cloth, the specimens were end-coated with hot paraffin wax and allowed to air-dry in a climatization room to achieve constant weights over a period of two months and to have the moisture content stabilized around 12%. After determining the volume, these air-dried samples were kept in an oven at 103±2°C until constant weights. The volume was again determined after coating with paraffin wax and volumetric shrinkage calculated.

Static bending and compressive strengths

Static bending test of air-dried 2 x 2 cm (cross section) and 30 cm long specimens was carried out using a 30 MT Universal Testing Machine (AMSLER/699/424, Switzerland). Deflections and the corresponding loads were recorded and load deflection curves prepared. Using the load deflection curves for air-dried specimens (2 x 2 cm cross section and 8 cm long), compressive stress at limit of proportionality, compressive stress at maximum load, and modulus of elasticity in compression parallel to grain were estimated. Likewise, from the load deflection curves for air dried 2 x 2 cm (cross-section) and 10 cm long specimens, compressive stress at limit of proportionality, crushing strength at maximum load, and modulus of elasticity in compression perpendicular to grain were computed.

Hardness

Hardness test was performed using the Brinel Hardness Testing Machine (No.59/65286-Switzerland) on air-dried 2 x 2 cm (cross section) and 10 cm long specimens. The load in kg required to penetrate a steel ball of 1.128 cm diameter into the specimen to half its diameter (0.564 cm) was taken as hardness. Hardness on the radial face, tangential face, and end surface of the specimens were determined.

Experimental data pertaining to various tests were analysed using analysis of variance in MSTAT (version 1.2) for comparing species, position of the specimens, and their interactions. Follow-up analysis (LSD Test) also was performed in MSTAT.

Results

Physical Properties

As expected, the differences in basic density and green moisture content were significant among species and positions along the radial direction (Table 1). Basic wood density followed the sequence: *A. auriculiformis* > *A. mangium* > *G. robusta,* while moisture content decreased in the order: *G. robusta* > *A. mangium* > *A. auriculiformis*. Wood density also increased from the inner to outer positions along the radial direction for the two acacias. Conversely, wood moisture content decreased from inner to the middle positions in *A. mangium*.

Mean radial, tangential, and volumetric shrinkages (green to air-dry and green to oven-dry) for *A. auriculiformis* were significantly lower than that of *A. mangium* and *G. robusta* (Table 1). While shrinkage values were not substantially different among the radial positions in *A. auriculiformis*, *G. robusta* exhibited the highest radial and tangential shrinkage for the 'outer' position. *A. mangium*, however, showed a reverse trend for tangential shrinkage, i.e., it increased from outer to inner positions. Volumetric shrinkage also decreased from inner to outer positions in *A. mangium,* but increased from inner to outer positions in *G. robusta*.

Mechanical Properties: Static bending strength

Fibre stress at limit of proportionality (FS at LP), modulus of rupture (MOR), modulus of elasticity (MOE), horizontal shear stress at limit of proportionality (HS at LP), and horizontal shear stress at maximum load (HS at ML) followed the order: *A. auriculiformis* > *A. mangium* > *G. robusta*. FS at LP increased significantly from inner to outer positions along the radial direction in *A. mangium*, while for other species it did not show a predictable pattern. *A. auriculiformis* specimens from the outer position showed a particularly high MOE compared to its inner and middle positions. It was, however, at par for the other two species.

Work to limit of proportionality (WK to LP), work to maximum load (WK to ML), and total work in static bending also followed the order: *A. auriculiformis* > *A. mangium* > *G. robusta*. WK to LP, however, did not show a consistent pattern with respect to positions. WK to ML was highest for the middle position in *A. auriculiformis*. But it increased from inner to outer position in *G. robusta*. Total work first increased from inner to middle position and then decreased modestly to the outer position in *A. auriculiformis*. Such differences were, however, not pronounced for *A. mangium* and *G. robusta*.

Compressive stress parallel to grain

Compressive stress at limit of proportionality (CS at LP), compressive stress at maximum load (CS at ML), and modulus of elasticity (MOE) in compression parallel to grain were highest for *A. auriculiformis*. The significant species x position interaction effects imply that CS at LP and ML, and MOE increased from inner to outer tissues in *A. mangium* and decreased progressively from inner to outer position in *G. robusta*. Sample positions, however, did not influence CS at LP and ML in *A. auriculiformis*, and MOE of *G. robusta*. Nonetheless, *A. auriculiformis* showed a slight increase in MOE from inner to middle positions.

Compressive stress perpendicular to grain

Species effect on compressive stress at limit of proportionality (CS at LP), compressive stress at maximum load (CS at ML), and modulus of elasticity (MOE) in compression perpendicular to grain was remarkable (Table 1). CS at LP, CS at ML, and MOE increased from inner to outer positions in *A. mangium*. However, in *A. auriculiformis* it increased modestly from inner to middle positions and decreased thereafter, although *G. robusta* depicted a divergent trend.

Table 1. Physical and mechanical properties of wood as influenced by species and position in the radial direction from pith to periphery for three multipurpose trees from Kerala.

Properties	Species	Inner	Middle	Outer	Mean
Basic density	*A. auriculiformis*	0.634^{a} (0.010)	0.636^{a} (0.009)	0.641^{a} (0.011)	0.637^{A} (0.017)
	A. mangium	0.477^{f} (0.005)	0.506^{d} (0.006)	0.517^{b} (0.005)	0.500^{B} (0.014)
	G. robusta	0.487^{e} (0.006)	0.489^{e} (0.006)	0.456^{g} (0.004)	0.478^{C} (0.013)
Green moisture content (%)	*A. auriculiformis*	40.54^{e} (1.13)	41.37^{e} (0.84)	40.90^{e} (1.03)	40.94^{C} (1.69)
	A. mangium	52.89^{ab} (1.03)	48.17^{cd} (0.78)	47.31^{d} (0.72)	49.46^{B} (2.03)
	G. robusta	51.58^{ab} (0.66)	50.41^{bc} (0.75)	53.27^{a} (0.87)	51.75^{A} (1.44)
Radial shrinkage green to air-dry (%)	*A. auriculiformis*	2.30^{f} (0.027)	2.33^{f} (0.027)	2.31^{f} (0.017)	2.31^{C} (0.04)
	A. mangium	3.61^{d} (0.02)	3.51^{de} (0.016)	3.42^{e} (0.03)	3.51^{B} (0.058)
	G. robusta	4.02^{c} (0.047)	4.19^{b} (0.06)	4.39^{a} (0.08)	4.20^{A} (0.139)
Radial shrinkage green to oven-dry (%)	*A. auriculiformis*	2.71^{e} (0.02)	2.71^{e} (0.013)	2.71^{e} (0.013)	2.71^{C} (0.029)
	A. mangium	3.97^{c} (0.027)	3.87^{cd} (0.023)	3.83^{d} (0.02)	3.89^{B} (0.052)
	G. robusta	4.69^{b} (0.063)	4.77^{b} (0.057)	5.04^{a} (0.097)	4.83^{A} (0.15)
Tangential shrinkage green to air-dry (%)	*A. auriculiformis*	4.91^{f} (0.023)	4.89^{f} (0.027)	4.89^{f} (0.02)	4.90^{C} (0.039)
	A. mangium	7.31^{d} (0.02)	7.23^{de} (0.022)	7.17^{e} (0.023)	7.24^{B} (0.05)
	G. robusta	7.64^{c} (0.053)	7.85^{b} (0.072)	7.96^{a} (0.039)	7.82^{A} (0.121)
Tangential shrinkage green to oven-dry (%)	*A. auriculiformis*	5.33^{e} (0.037)	5.37^{e} (0.023)	5.38^{e} (0.023)	5.36^{C} (0.052)
	A. mangium	7.69^{c} (0.013)	7.61^{cd} (0.017)	7.56^{d} (0.017)	7.62^{B} (0.04)
	G. robusta	8.54^{b} (0.063)	8.91^{a} (0.047)	8.98^{a} (0.04)	8.81^{A} (0.139)
Volumetric shrinkage green to air-dry (%)	*A. auriculiformis*	6.40^{e} (0.07)	6.37^{e} (0.123)	6.58^{e} (0.09)	6.45^{C} (0.167)
	A. mangium	7.71^{c} (0.05)	7.38^{d} (0.06)	7.30^{d} (0.04)	7.47^{B} (0.133)
	G. robusta	9.29^{b} (0.087)	9.39^{ab} (0.073)	9.62^{a} (0.133)	9.44^{A} (0.191)
Volumetric shrinkage green to oven dry (%)	*A. auriculiformis*	6.79^{e} (0.093)	6.75^{e} (0.113)	6.84^{e} (0.107)	6.80^{C} (0.26)
	A. mangium	7.97^{c} (0.057)	7.66^{d} (0.063)	7.56^{d} (0.06)	7.73^{B} (0.144)
	G. robusta	9.56^{b} (0.103)	9.66^{ab} (0.083)	9.91^{a} (0.133)	9.71^{A} (0.202)
Fibre stress at limit of proportionality (kg cm^{-2})	*A. auriculiformis*	578.9^{a} (21.7)	575.4^{a} (20.1)	576.3^{a} (12.8)	576.9^{A} (31.0)
	A. mangium	390.8^{c} (16.0)	414.2^{bc} (17.1)	450.7^{b} (14.3)	418.6^{B} (30.8)
	G. robusta	199.9^{d} (16.8)	176.4^{d} (14.7)	175.7^{d} (13.2)	184.0^{C} (25.8)
Modulus of rupture in static bending[1] (kg cm^{-2})	*A. auriculiformis*	664.3	740.2	795.6	733.4^{A} (38.0)
	A. mangium	590.6	622.6	498.6	570.6^{B} (37.2)
	G. robusta	241.1	205.3	307.1	251.2^{C} (29.8)
Modulus of elasticity in static bending (kg cm^{-2})	*A. auriculiformis*	78473^{b} (6005)	77244^{b} (6504)	102276^{a} (8491)	85998^{A} (13596)
	A. mangium	84697^{b} (6210)	75363^{b} (3863)	80641^{b} (5475)	80234^{A} (9061)
	G. robusta	25265^{c} (2497)	26240^{c} (2687)	26564^{c} (1851)	26023^{B} (3961)
Horizontal shear stress on neutral plane at limit of proportionality (kg cm^{-2})	*A. auriculiformis*	22.03^{a} (0.76)	21.89^{a} (0.68)	22.18^{a} (0.50)	22.04^{A} (1.09)
	A. mangium	14.59^{c} (0.52)	15.64^{c} (0.62)	17.17^{b} (0.54)	15.80^{B} (1.12)
	G. robusta	7.85^{d} (0.66)	6.95^{d} (0.58)	6.90^{d} (0.52)	7.23^{C} (1.02)
Horizontal shear stress at maximum load in static bending[1] (kg cm^{-2})	*A. auriculiformis*	25.27	27.87	30.92	28.02^{A} (1.33)
	A. mangium	19.6	20.31	24.64	21.52^{B} (1.29)
	G. robusta	7.18	10.37	12.09	9.88^{C} (1.17)
Work to limit of proportionality in static bending (kg cm cm^{-3})	*A. auriculiformis*	0.234^{a} (0.02)	0.242^{a} (0.016)	0.193^{b} (0.022)	0.223^{A} (0.035)
	A. mangium	0.098^{d} (0.008)	0.121^{cd} (0.012)	0.134^{c} (0.01)	0.118^{B} (0.019)
	G. robusta	0.096^{d} (0.018)	0.065^{e} (0.008)	0.066^{e} (0.01)	0.076^{C} (0.023)
Work to maximum load in static bending (kg cm cm^{-3})	*A. auriculiformis*	0.690^{b} (0.108)	0.896^{a} (0.134)	0.639^{b} (0.119)	0.742^{A} (0.209)
	A. mangium	0.412^{c} (0.034)	0.494^{c} (0.066)	0.436^{c} (0.028)	0.447^{B} (0.079)
	G. robusta	0.352^{cd} (0.05)	0.247^{de} (0.032)	0.183^{e} (0.03)	0.261^{C} (0.076)

Total work in static bending (kg cm cm^{-3})	*A. auriculiformis*	0.947^{bc} (0.137)	1.307^{a} (0.145)	1.134^{ab} (0.159)	1.129^{A} (0.259)
	A. mangium	0.892^{bc} (0.07)	0.867^{c} (0.087)	0.976^{bc} (0.091)	0.912^{B} (0.141)
	G. robusta	0.611^{d} (0.064)	0.480^{d} (0.07)	0.419^{d} (0.072)	0.504^{C} (0.124)
Compressive stress at limit of proportionality in compression parallel to grain (kg cm^{-2})	*A. auriculiformis*	395.0^{a} (13.1)	396.5^{a} (15.6)	398.3^{a} (7.0)	396.6^{A} (20.7)
	A. mangium	236.5^{c} (11.2)	247.5^{c} (12.0)	274.5^{b} (11.7)	252.8^{B} (21.5)
	G. robusta	171.9^{d} (6.1)	162.4^{de} (6.3)	144.0^{e} (4.0)	159.5^{C} (11.5)
Compressive stress at maximum load in compression parallel to grain (kg cm^{-2})	*A. auriculiformis*	451.7^{a} (11.3)	447.9^{a} (15.0)	439.2^{a} (10.2)	446.3^{A} (20.7)
	A. mangium	308.4^{c} (18.9)	320.6^{bc} (20.5)	340.5^{b} (13.8)	323.2^{B} (30.9)
	G. robusta	224.5^{d} (6.8)	219.9^{d} (8.8)	205.2^{d} (6.5)	216.5^{C} (13.3)
Modulus of elasticity in compression parallel to grain (kg cm^{-2})	*A. auriculiformis*	68837^{ab} (3820)	78093^{a} (4487)	72646^{a} (2607)	73192^{A} (7221)
	A. mangium	49362^{c} (3169)	60496^{b} (4378)	72492^{a} (3965)	60784^{B} (8393)
	G. robusta	22024^{d} (786)	22335^{d} (808)	22091^{d} (872)	22149^{C} (1371)
Compressive stress at limit of proportionality in compression perpendicular to grain (kg cm^{-2})	*A. auriculiformis*	135.4^{ab} (8.3)	139.5^{a} (6.7)	124.1^{b} (5.8)	133.0^{A} (12.3)
	A. mangium	61.7^{e} (5.1)	78.6^{d} (3.6)	93.4^{c} (5.8)	77.9^{B} (11.2)
	G. robusta	40.2^{f} (2.0)	30.5^{f} (2.0)	30.0^{f} (3.2)	33.6^{C} (5.0)
Compressive stress at maximum load in compression perpendicular to grain (kg cm^{-2})	*A. auriculiformis*	486.8^{a} (6.5)	496.1^{a} (12.0)	489.2^{a} (9.4)	490.7^{A} (16.1)
	A. mangium	336.0^{c} (11.4)	370.6^{b} (10.5)	382.8^{b} (10.3)	363.1^{B} (21.3)
	G. robusta	279.8^{d} (5.8)	271.0^{de} (5.9)	253.3^{e} (6.1)	268.0^{C} (11.8)
Modulus of elasticity in compression perpendicular to grain (kg cm^{-2})	*A. auriculiformis*	69165^{ab} (3037)	74387^{a} (6287)	71913^{ab} (5537)	71822^{A} (8653)
	A. mangium	53546^{c} (4033)	62565^{bc} (2962)	69395^{ab} (3346)	61836^{B} (6931)
	G. robusta	30620^{d} (2586)	24318^{d} (1600)	20673^{e} (1398)	25204^{C} (4011)
Hardness in radial plane (kg)	*A. auriculiformis*	381.7^{b} (18.0)	415.6^{a} (5.7)	383.3^{b} (8.0)	393.5^{A} (21.8)
	A. mangium	207.8^{cd} (12.5)	220.0^{cd} (9.7)	226.1^{c} (11.1)	218.0^{B} (19.2)
	G. robusta	209.4^{cd} (4.9)	203.9^{d} (5.9)	212.8^{cd} (7.3)	208.7^{B} (10.4)
Hardness in tangential plane (kg)	*A. auriculiformis*	432.8^{b} (17.3)	461.7^{a} (7.3)	397.2^{c} (6.5)	430.6^{A} (24.6)
	A. mangium	232.8^{de} (13.4)	247.2^{d} (12.0)	247.8^{d} (11.5)	242.6^{B} (20.9)
	G. robusta	220.6^{e} (5.6)	214.4^{e} (5.0)	216.7^{e} (9.3)	217.0^{C} (11.5)
End-hardness (kg)	*A. auriculiformis*	685.0^{a} (12.0)	673.9^{ab} (10.3)	644.4^{b} (11.8)	667.8^{A} (21.5)
	A. mangium	358.3^{d} (9.7)	395.6^{c} (21.6)	405.0^{c} (12.9)	386.3^{B} (37.0)
	G. robusta	324.4^{e} (5.9)	331.1^{de} (8.2)	320.0^{e} (6.7)	325.2^{C} (12.0)

Values with the same alphabetical superscripts do not differ significantly; upper case superscripts (last column) compare marginal means and lower case contrasts species x position interaction effects; [1]species x position interaction effects not significant, while in all other cases such interactions were significant; Values in parenthesis are standard errors (n=9 for sample positions).

Hardness

Hardness in radial and tangential planes, besides end surface hardness of *A. auriculiformis* was higher than that of *A. mangium* and *G. robusta*. Wood specimens from the mid position of *A. auriculiformis* had significantly higher radial and tangential hardness values than that of inner and outer positions, while the other species did not show any predictable pattern. End-hardness decreased progressively from inner to outer positions in *A. auriculiformis* but *A. mangium* showed a divergent pattern. A modest increase from inner to middle wood and a slight decrease thereafter from mid to outer wood were observed in *G. robusta*.

Discussion and Conclusions

Overall, the physical and mechanical properties of *A. auriculiformis* were superior to that of *A. mangium* and *G. robusta*. Considering the fact that age of the sampled trees (10 to 15 years) and site characteristics (all extracted from the agricultural lands of central Kerala) were mostly similar, it seems reasonable to assume that the high variability observed may be on account of intrinsic genetic factors. The relatively modest standard errors (Table 1) further exemplify the lack of profound within species variations even between apparently disparate sampling locations (e.g, Peerumedu and Perumbavoor for *G. robusta*). A comparison of the present data with that from other locations (published literature) also suggests that agroforestry situations *per se* do not exert any negative impact on wood properties. Indeed, most physical and mechanical properties reported presently are within the range of values reported in the literature. For instance, specific gravity of the 15-year-old *A. auriculiformis* trees (0.637) sampled in this study is comparable to that of 10-year-old trees from Bihar (0.623; Shukla et al., 1990). Likewise, *A. mangium* had a mean specific gravity (0.500) close to that (0.508) reported by Dhamodaran and Chacko (1999). Mean moisture content reported presently (Table 2) is, however, lower than that of the values reported by Kumar et al. (1987) for *A. auriculiformis* (48.1%) and Khanduri et al. (2000) for *G. robusta* (90.3%). This is not surprising in view of the fact that season of sample collection play an important role in determining wood moisture content. In the present study, the samples were collected during March (summer), which might have resulted in relatively lower wood moisture levels. Furthermore, mechanical properties such as radial and tangential shrinkages (green to oven-dry) of *A. auriculiformis*, and tangential (green to air-dry) and radial and tangential shrinkages (green to oven-dry) of *A. mangium,* and the radial, tangential, and volumetric shrinkage (green to air-dry) of *G. robusta* were comparable to the values reported by Shukla et al. (1990), Dhamodaran and Chacko (1990), and Khanduri et al. (2000) for the respective species.

Variations in shrinkage and surface hardness from inner to outer positions in the radial direction for *A. mangium* and *G. robusta* followed a trend similar to that of wood moisture content and basic density respectively implying interrelationships between physical and mechanical properties. Compression parallel to grain from inner to outer positions for all the three species also varied with wood density. Variations in static bending properties from inner to outer tissue samples for the three species showed that modulus of elasticity in *A. auriculiformis*; fibre stress at limit of proportionality, horizontal shear stress at limit of proportionality, and work to limit of proportionality in *A. mangium*; and work to maximum load in *G. robusta* followed a trend similar to that of wood density. Several previous workers too reported such interdependence among specific gravity, shrinkage, and strength properties (Ilic, 1999; Shanavas and Kumar, 2003). Other static bending properties *viz.* work to limit of proportionality, work to maximum load, and total work in *A. auriculiformis* and work to limit of proportionality in *G. robusta*, however, did not show much correspondence with wood density.

As regards to the effect of radial position on the physical and mechanical properties of wood, differences were generally not significant for *A. auriculiformis* implying that physical/mechanical properties of wood were less variable along the radial direction in this species. However, increase in specific gravity from inner to outer position was observed in *A. mangium*, which is consistent with the findings of Sulaiman (1993). Conversely, *G. robusta* showed a modest reduction in specific gravity of the outer wood specimens with corresponding variations in the mechanical properties of wood. Benny and Bhat (1996) reported similar observations for *Eucalyptus grandis*.

A comparison of the physical and mechanical properties of the three focal species with teak (Table 2) indicates that *A. auriculiformis* had higher wood basic density, work to limit of proportionality in static bending, work to maximum load in static bending, compressive stress at limit of proportionality in parallel to grain, compressive stress at limit of proportionality (parallel and perpendicular to grain), and end-hardness than teak. Nonetheless, *A. auriculiformis* was inferior to teak in many other aspects. All physical and mechanical properties of *A. mangium* and *G. robusta* were also inferior to teak, except shrinkage.

This study further reinforces the fact that agroforestry systems in general and the three focal species in particular could be potential sources of commercial timber, especially in a state like Kerala, where such woody perennial based land use systems abound. Since wood properties of trees from the agricultural lands are generally overlooked by researchers, results of the present study may be useful in the choice of species for establishing agroforestry plantations and/or for reintroducing trees into the homegarden system. However, the values reported for a given species reflect

Table 2. A comparative account on the physical and mechanical properties of fast growing multipurpose trees with teak.

Properties	*A. auriculiformis*	*A. mangium*	*G. robusta*	*Tectona grandis*[1]
Basic density	0.637	0.50	0.478	0.604
Moisture content green to oven-dry (%)	40.94	49.46	51.75	76.6
Radial shrinkage green to air-dry (%)	2.312	3.512	4.196	2.3
Tangential shrinkage green to air-dry (%)	4.895	7.236	7.817	4.8
Volumetric shrinkage green to air-dry (%)	6.449	7.466	9.435	6.9
Fibre stress at limit of proportionality (kg cm^{-2})	576.9	418.6	184.0	651
Modulus of rupture (kg cm^{-2})	733.4	570.6	251.2	959
Modulus of elasticity (kg cm^{-2})	85998	80234	26023	119060
Work to limit of proportionality (kg cm cm^{-3})	0.223	0.118	0.076	0.200
Work to maximum load (kg cm cm^{-3})	0.742	0.447	0.261	0.720
Total work (kg cm cm^{-3})	1.129	0.912	0.504	1.41
Compressive stress parallel to grain at limit of proportionality (kg cm^{-2})	396.6	252.8	159.5	376
Maximum crushing stress (kg cm^{-2})	446.3	323.2	216.5	532
Modulus of elasticity (kg cm^{-2})	73192	60784	22149	137400
Compressive stress perpendicular to grain at limit of proportionality (kg cm^{-2})	133.01	77.86	33.56	101
Hardness				
Radial (kg)	393.5	218.0	208.7	502
Tangential (kg)	430.6	242.6	217.0	524
End (kg)	667.8	386.3	325.2	488

[1]from Malabar, Nilambur, and Coimbatore (source: Sekhar and Rawat, 1966).

only the samples tested and not the entire population of these species. Yet another limitation of this study is that samples from a wide range of situations including forest plantations have not been tested.

Acknowledgements

Facilities for testing the samples provided by the Professor and Head, Department of Civil Engineering, College of Engineering, Thrissur and the technical guidance rendered by Dr. R. Gnanaharan, Kerala Forest Research Institute, Peechi are gratefully acknowledged. This research formed part of the MSc (Forestry) thesis submitted to the Kerala Agricultural University, India, by the senior author.

References

Benny, A.G. and Bhat, K.M. 1996. Strength properties of *Eucalyptus grandis* grown in low and high altitudinal localities in Kerala. J. Timb. Dev. Assoc., 42(2): 33–38.

Bhat, K.M. 2005. Quality concerns of sustainable teak wood chain. In: Bhat, K.M., Nair, K.K.N., Bhat, K.V., Muralidharan, E.M., and Sharma J.K. (eds), *Quality Timber Products of Teak from Sustainable Forest Management*. Kerala Forest Research Institute, Peechi and ITTO, Japan, pp 228–242.

BIS 1986. *Method of testing small clear specimens of timber*. IS 1708, Bureau of Indian Standards, New Delhi, 42p.

Dhamodaran, T.K. and Chacko, K.C. 1999. Growth and wood characteristics of *Acacia mangium* grown in Kerala. Research Report No.174, Kerala Forest Research Institute, Peechi, 60p.

Ilic, J. 1999. Shrinkage related degrade and its association with some physical properties in *Eucalyptus regnans* F. Muell. Wood Sci. Technol., 33: 425–437.

Khanduri, A.K., Panwar, P.S., and Jain, J.D. 2000. An assessment of physical and mechanical properties of plantation grown *Grevillea robusta* and *Terminalia myriocarpa*. J. Timb. Dev. Assoc., 46(3): 19–27.

Kumar, B.M. 2005. Land use in Kerala: changing scenarios and shifting paradigms. J. trop. Agric., 43: 1–12.

Kumar, B.M., George, S.J., and Chinnamani, S. 1994. Diversity, structure, and standing stock of wood in the homegardens of Kerala in Peninsular India. Agroforest. Syst., 25: 243–262.

Kumar, P., Ananthanarayanan, A.K., and Sharma, S.N. 1987. Physical and mechanical properties of *Acacia auriculiformis* from Karnataka. Indian For., 113: 567–573.

Pandey, D. and Brown, C. 2000. Teak: a global overview. Unasylva, 51: 3–13.

Scharai, R.M. and Kambey, E. 1989. The wood of *Acacia mangium* Willd: its properties and possible uses. GFG report, German Forestry Group, Mulawarman University, Kalimanthan, Indonesia, p 62.

Sekhar, A.C. and Rawat, B.S. 1966. Physical and mechanical properties of teak from different localities in India and neighbouring areas. Indian For. Rec. (Timb. Mech.), 1 (13): 197–212.

Shanavas, A. and Kumar, B.M. 2003. Fuelwood characteristics of tree species in the homegardens of Kerala, India. Agroforest. Syst., 58: 11–24.

Shukla, N.K., Lal, M., Singh, R.S. and Khanduri, A.K. 1990. Physical and mechanical properties of *Acacia auriculiformis*, *Fernandoa adenophylla* and *Melia azaderach*. J. Timb. Dev. Assoc., 36 (2): 31–45.

Shukla, S.R., Sudheendra, R., and Rao, R.V. 1999. Preliminary studies on physical and mechanical properties of plantation grown Andaman Padauk (*Pterocarpus dalbergioides*) from Karnataka. J. Timb. Dev. Assoc., 45 (1-2): 1 –15.

Sulaiman, A. 1993. Variation in specific gravity of five-year-old *Acacia mangium* from the Batu Arang Plantation, Malaysia. J. Trop. For. Sci., 6: 203–206.