A reassessment of the compressive strength properties of southern yellow pine bark

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Abstract

Samples of southern yellow pine outer bark and wood were tested in compression to determine values for modulus of elasticity, stress at proportional limit, and maximum crushing strength. Results reported here resolve inconsistencies in the compressive strength data previously reported by others for pine bark. Testing of solvent-treated bark blocks suggests that although extractives are present in significant amounts, their contribution to the mechanical properties is minimal.

Bark comprises roughly 10 to 20 percent of a tree stem with higher amounts for the branches in the crown (Fengel and Wegener 1983). The inner bark (phloem), as the conductive tissue necessary for transporting the products of photosynthesis, is protected by the outer bark (rhytidome) which includes the mostly nonliving tissues outside the innermost periderm. Differences in the basic anatomy between bark and wood are manifested in differences in their mechanical properties. In a recent study, the stiffness of the bark was one half that of the respective wood; however, it was found that the bark contributed significantly to the resistance of stem segments to bending forces (Niklas 1999). The mechanical properties of bark are also important for practical reasons since bark has been suggested as a resource for composite manufacture (Maloney 1973, Chow 1975, Blanchet et al. 2000). Nevertheless, only a few studies have focused on the mechanical properties of bark. Whereas the radial compressive strength of Douglas-fir (*Pseudotsuga menziesii* Franco) bark was significantly lower relative to that in the longitudinal direction (Lin 1973), a study including several southern pine species (e.g., *P. taeda* L., *P. echinata* Mill., *P. palustris* Mill., *P. elliottii* Engelm.) suggested that the compressive strength in the radial direction was equal or higher than that in the other directions (tangential, longitudinal), especially at higher bark SGs (Martin and Crist 1968). To address this inconsistency, a study was undertaken to determine the compressive strength of southern yellow pine (SYP) bark. Since the extractives in wood may influence wood mechanical properties to a limited extent (Panshin and de Zeeuw 1980, Wood Handbook 1999), solvent-treated bark specimens were tested in an effort to determine if the high extractives content of the bark influences the compressive strength properties.

Materials and methods

Sample preparation

Freshly-peeled SYP bark (essentially all *Pinus taeda* L.) was collected near the debarking station at a local plywood plant and allowed to dry under ambient conditions. The largest pieces were selected and cut into small square sections (*ca.* 10 by 10 mm) with a band saw. A razor blade was then used to level the outer surface, and on the opposite side, remove the inner bark. Fine sandpaper was used to remove rough edges and square the blocks. The thickness of the air-dry bark blocks ranged from about 2 to 5 mm. All blocks were marked with a soft lead pencil, weighed, and all dimensions then measured with a digital caliper. Samples of SYP wood were cut into blocks for use as controls. The small wood blocks (10 by 10 by 10 mm) were cut from a finely grained board that provided four growth rings for each cross section. Larger wood blocks were prepared for testing perpendicular to the grain (38 by 38 mm cross section and 140 mm length) and parallel to the grain (25 by 25 mm cross section and 100 mm length); in the latter case, the specimens had four growth rings for each cross section. All bark and wood blocks were conditioned in the testing laboratory for 1 month before mechanical testing. Every effort was made to maintain the temperature (23 °C) and the humidity (50%) close to those used elsewhere for the testing of bark in compression (Lin 1973).

Mechanical testing

Bark blocks were tested in compression using an Instron (Norwood, Massachusetts, USA) Universal Materials Testing Machine (Model 4465) equipped with a 5 kN load cell. Wood blocks were tested in the same manner except when the capacity of the load cell was likely to be exceeded; these blocks

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Table 1. — Physical and mechanical properties of SYP bark and wood blocks.

Specimen type	Treatment	Specimen size[a]	Testing orientation[b]	SG before extraction	Weight loss	SG after extraction	Modulus of elasticity	Stress at proportional limit	Maximum crushing strength
					(%)		(MPa)		
Bark	No solvent treatment	A	Radial	0.54 ± 0.10	na[c]	na	18 ± 5.3	0.7 ± 0.5	nd[c]
			Tangential	0.63 ± 0.06	na	na	140 ± 65	3.5 ± 0.9	4.5 ± 0.7
			Longitudinal	0.67 ± 0.10	na	na	350 ± 130	9.1 ± 3.4	12 ± 2.5
	Rapid solvent treatment	A	Radial	0.57 ± 0.08	1.2 ± 0.3	0.60 ± 0.08	16 ± 5.7	0.8 ± 0.3	nd
			Tangential	0.58 ± 0.06	0.7 ± 4.0	0.60 ± 0.06	200 ± 62	4.0 ± 1.1	5.1 ± 1.2
			Longitudinal	0.55 ± 0.08	2.0 ± 2.3	0.58 ± 0.08	370 ± 97	8.6 ± 2.3	11 ± 2.4
	Extended solvent treatment	A	Radial	0.58 ± 0.08	4.0 ± 1.3	0.54 ± 0.10	18 ± 8.2	0.7 ± 0.4	nd
			Tangential	0.55 ± 0.03	4.1 ± 2.6	0.55 ± 0.04	200 ± 95	3.8 ± 1.9	5.2 ± 2.6
			Longitudinal	0.55 ± 0.05	5.2 ± 1.9	0.55 ± 0.07	360 ± 120	7.3 ± 1.8	9.4 ± 1.9
Wood	No solvent treatment	B	Radial	0.68 ± 0.01	na	na	170 ± 45	2.8 ± 0.6	nd
			Tangential	0.68 ± 0.01	na	na	380 ± 87	2.8 ± 0.5	5.5 ± 0.6
			Longitudinal	0.67 ± 0.01	na	na	2400 ± 620[d]	34 ± 5.3[d]	49 ± 2.8[d]
		C	Perpendicular	0.52 ± 0.01	na	na	400 ± 41[d]	2.4 ± 0.3[d]	nd
		D	Longitudinal	0.51 ± 0.02	na	na	3400 ± 480[d]	21 ± 4.3[d]	30 ± 5.8[d]

[a]Approximate sizes of specimens: A is 10 by 10 mm with a 2- to 5-mm thickness (radial direction); B is 10 by 10 by 10 mm; C is 38- by 38-mm cross section and 140-mm length; D is 25- by 25-mm cross section and 100-mm length.
[b]Ten or more specimens ($n \geq 10$) were tested for specimen type, treatment, and size for each testing orientation.
[c]na = not applicable; nd = not definitive.
[d]150 kN load cell was used instead of 5 kN load cell.

were instead tested with an Instron (Model 4206) equipped with a 150 kN load cell. Conditioned samples were carefully centered between the platens and compressed using a crosshead speed of 1.27 mm per minute. The small size of the specimens necessitated using the distance that the load cell traveled as the measure of the test specimen deformation. Values for modulus of elasticity were determined from the slopes of the load-deformation curves. MCs (dry weight basis) for the bark (10.8 ± 0.3%) and wood (8.7 ± 0.1%) specimens were determined after mechanical testing by drying grouped specimens in an oven at 103 ± 2 °C.

Solvent extraction

Bark blocks were divided to provide three sets with 30 blocks in each set. The first set of blocks was retained as a control. The second set of blocks (*ca.* 10 g total weight) was submerged in a mixture of acetone:water (7:3, 200 mL) for 10 minutes during which infiltration was promoted by applying and releasing a vacuum with an aspirator. The blocks were subsequently removed from the solvent and allowed to dry under ambient conditions before weighing and measuring their dimensions. The remaining solvent was evaporated to afford a very small amount of dry residue (8 mg). The third set of blocks was submerged in the solvent mixture for 24 hours, with a vacuum applied over the first 10 minutes, as before, to promote infiltration. The solvent was decanted and evaporated to afford a dry extract (218 mg). The 24-hour steeping process was repeated two times to afford two additional extracts (second extract, 94 mg; third extract, 62 mg). The blocks were allowed to dry under ambient conditions before weighing and measuring their dimensions; all solvent-treated bark blocks were conditioned along with the control (i.e., unextracted) bark blocks before mechanical testing. Extra bark blocks, processed in parallel, were dried in an oven (103 ± 2 °C) to determine values for MC.

Inadequately-sized bark blocks were ground in a Wiley mill equipped with a 10-mesh screen. An aliquot of the resultant bark meal (8 g) was steeped in acetone:water (7:3, 100 mL) as above with the solvent exchanged after 24 and 48 hours by vacuum filtration with a Büchner funnel. All filtrates were evaporated to afford dry extracts (first extract, 643 mg; second extract, 82 mg; third extract, 43 mg).

Results and discussion

Mechanical testing of bark blocks

Results from the mechanical testing of the bark blocks showed each mechanical property to be the highest in the longitudinal direction with the values in the tangential direction being substantially lower (**Table 1**). Bark blocks tested in the radial direction gave very low values for both the modulus of elasticity and the stress at proportional limit. Values for maximum crushing strength could not be obtained under the conditions employed since the spongy obliterated phloem tissues between the periderm tissues were so weak, and failed continuously, that an abrupt mechanical failure could not be recorded. These findings were in stark contrast to an earlier report for various species of pine bark where the maximum crushing strength in the radial direction was significantly higher than that in both the longitudinal and tangential orientations for samples with similar SGs (Martin and Crist 1968). It was also suggested that the maximum crushing strength was correlated ($r^2 = 0.80$) with the SG in the radial, but not the longitudinal or tangential orientations. Regression analysis of the data from the current study showed the maximum crushing strength to be correlated with SG when the samples were in the longitudinal ($r^2 = 0.82$) and tangential ($r^2 = 0.79$) directions. For Douglas-fir bark, significantly higher values for modulus of elasticity, stress at proportional limit, and maximum crushing strength were reported in the longitudinal direction, as compared to the radial and tangential directions (Lin 1973). Given the anatomical features of SYP outer bark (Howard 1971), the data reported in the current study appear to be more representative. It should be noted that in the prior

study, inner bark may have been present on some of the bark specimens subjected to mechanical testing (Martin and Crist 1968). Nevertheless, given the anatomical features of SYP inner bark, it is difficult to rationalize how the compressive strength could have been determined to be the highest in the radial direction.

Mechanical testing of wood blocks

Since bark is not as amenable to mechanical testing as wood, in both this and earlier studies, the specimens were not all of uniform size. Another caveat is that the dimensions of the bark blocks are small relative to those used for the mechanical testing of wood. To address this issue, small blocks of SYP wood were tested along with standard-sized blocks (ASTM 2005) for comparison. To provide data for a direct comparison, the testing procedure was modified so that the steel plate covered the entire specimen width. Testing of the small wood blocks gave values that were substantially higher than those for the bark (**Table 1**). Similar to the bark specimens, meaningful values for maximum crushing strength could not be determined for the wood specimens tested in the radial direction because of continuous densification as the stress increased beyond the proportional limit. Unlike the bark, the values for each of the compressive strength properties for the wood showed greater similarity in the tangential and radial directions. The high compressive strength properties of the wood in the longitudinal direction required the use of a testing machine with a higher capacity load cell. Similarity in the values obtained from the small specimens with those of a standard size suggested that although it is not the ideal practice, the mechanical testing of small specimens can give representative data.

Extractive yields

SYP bark is a rich source of both hydrophilic extractives (e.g., proanthocyanidin polymers) and lipophilic extractives (e.g., resin acids, fatty acids). A mixture of acetone:water was selected as the extraction solvent for this study since it had previously been used to remove proanthocyanidin polymers for characterization studies (Foo and Porter 1980, Eberhardt and Young 1994), and although not targeted for such studies, also removes lipophilic extractives. Steeping at room temperature, as usually done with this solvent mixture, was preferred to avoid temperature-related changes that may occur during Soxhlet extraction. Steeping the bark blocks over a 3-day period afforded a total extractives yield of 3.9 percent which was very close to the weight change (**Table 1**) measured for the blocks receiving this treatment. A rapid treatment with the same solvent mixture afforded a total extractives yield of less than 0.1 percent; a loss in weight greater than this amount was attributed to small changes in MC during processing. Extraction of a sample of bark meal afforded a total extractives yield of 10.8 percent. Assuming that the grinding process only improved the extraction efficiency, steeping the bark in the form of blocks, as described above, allowed the removal of less than one half of the potentially available bark extractives.

Mechanical testing of solvent-treated bark blocks

The SGs of the bark blocks both before and after the solvent treatments were essentially identical (**Table 1**). Thus, for the solvent-treated bark blocks, a reduction in volume accompanied the loss in weight from the removal of some of the extractives. Bark blocks subjected to the rapid and extended solvent treatments were also subjected to mechanical testing and generally showed values similar to those for the untreated bark blocks, especially in the tangential and radial directions. The values for the stress at proportional limit and maximum crushing strength collected in the longitudinal direction appeared to decrease with the solvent treatments, however, the differences between the treatments were not statistically significant when compared by analysis of variance. Analogous to wood, the bark extractives that are readily removed may only provide a small, if any, influence over the mechanical properties. Several pine barks have been shown to contain proanthocyanidins (condensed tannins) that are not readily removed by extraction (Matthews et al. 1997). Since these extractives may become bound to the cell wall matrix (Matthews et al. 1997), it is possible that certain extractives may ultimately contribute to the mechanical properties of bark as such modifications occur.

Conclusions

The compressive strength of SYP bark, like wood, is greatest in the longitudinal direction. It is likely that contradictory findings appearing in an earlier report resulted from an inability to detect the mechanical failure of the very fragile obliterated phloem tissues in pine bark, as well as challenges associated with the testing of small blocks of different dimensions. Results from the mechanical testing of solvent-treated bark blocks suggest that although extractives are present in significant amounts, their contribution to the compressive strength properties are minimal. However, it remains to be determined if the conversion of certain extractives to insoluble forms, as suggested for the proanthocyanidins, ultimately results in a significant influence over the mechanical properties.

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