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Effect of Brown-rotted Wood on Mechanical Properties and Ultrasonic Velocity*1

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ABSTRACT

Artificial brown-rot decay was induced to two wood species, *Pinus densiflora* and *Pinus radiata*. A modified direct inoculation method was used and the decay indicators of mass loss and two compressive mechanical properties, maximum compressive strength (MCS) and compressive stiffness, were estimated over the period of 8 weeks of fungal exposure. Measurable mass loss occurred 2 weeks after the fungal attack, with 15% to 22% of the loss occurring 8 weeks after fungal exposure with *Fomitopsis palustris* and *Gloeophyllum trabeum*. Mechanical properties proved to be far more sensitive than mass loss detection: approximately five to six times by quantity. Of the two mechanical properties, MCS was more sensitive to and consistent with progressive brown-rot decay. An ultrasonic test was performed to determine the feasibility and accuracy of this method for nondestructive detection of brown-rot decay. The ultrasonic test is highly sensitive at qualitative detection of the early stages of brown-rot decay.

Keywords : brown-rot fungi, maximum compressive strength (MCS), compressive stiffness, mass loss, ultrasonic test

1. INTRODUCTION

Wood is one of the most common materials in construction and has been used closely related to the history of man. Although wood has many beneficial properties, such as a relatively high specific strength and workability, bio-deterioration due to the factors such as termites, insects, and fungi can cause severe problems, particularly for wooden structures constructed outdoors (Lee *et al.*, 2003). In order to preserve culturally important structures constructed using wood, scientific methodology related to the detection and prevention of these defects must be established. Related studies have been performed by several wood scientists (Kim and Lee, 2005). Specifically, a computed tomography (CT) technique using X-ray and ultrasonic tests was applied to enable the visualization of the internal state of structural members, such as columns and beams (Tamura *et al.*, 1997; Adachi *et*

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Table 1. Average density and standard deviation for each group of test specimens based on constant weight before fungal exposure

	Pinus densiflora			*Pinus radiata*		
	Fomitopsis palustris	*Gloeophyllum trabeum*	Control	*Fomitopsis palustris*	*Gloeophyllum trabeum*	Control
No. of specimen (pieces)	64	64	8	64	64	8
Mean density (g/cm^3)	0.46	0.48	0.47	0.45	0.48	0.47
Standard Deviation	0.039	0.042	0.032	0.034	0.072	0.074

al., 1999; Yanagida *et al.*, 2007). For ultrasonic tests, consideration of the anisotropic property of wood enables the reconstruction of a more exact CT image (Kim *et al.*, 2007). However, wood has many non-homogeneous natural defects, such as knots, cracks and pockets, and these are refractory to exact visualization; moreover, it is very hard to distinguish these defects from bio-deterioration and an exact scientific criterion to determine the initial stage of bio-deterioration has yet to be established.

There has been previous research related to the detection of bio-deterioration caused by brown-rot fungi (Kim *et al.*, 1996; Winandy *et al.*, 2000; Machek *et al.*, 2001). The direct inoculation method was usually used as an accelerated decay test (Curling *et al.*, 2002). In this method, artificial decay normally started at the mid-part of the specimen which was prepared for the bending test. A bending strength loss of over 30% occurred, compared to a mass loss of only 5% at the deteriorated part; the rate of strength loss is more sensitive by five times than that of mass loss by quantity. A similar research that used a direct inoculation method tested various wood composites (Illman *et al.*, 2002). A research has focused not only on the weight and strength properties of the wood, but also on its chemical composition and anatomical changes (Clausen *et al.*, 2003).

This research was performed as a part of larger study which intends to establish scientific criteria for the detection and prevention of biodegradation of column members in ancient wooden buildings. From the various causes of the bio-deterioration, brown-rot decay was studied because serious strength loss even during the initial stages of decay can be occurred by brown-rot fungi. Changes of mechanical properties in compressive manner were related to the mass loss which is caused by brown-rot decay because column members mainly effected by the axial force. The ultrasonic test was considered as the Nondestructive evaluation (NDE) method and the feasibility of detecting decay was found out with the simple Time-of-Flight (TOF) analysis.

2. MATERIALS and METHODS

2.1. Materials

Two species of wood, *Pinus Densiflora* and *Pinus Radiata*, without visually detectable knots, splits, or other defects were prepared. The specimen size was 100 mm (thickness) by 30 mm (width) by 100 mm (length), and specimens were sawed tangentially, radially, and longitudinally, respectively (Fig. 2). These sizes were determined for ultrasonic test at the radial direction and compressive test at the longitudinal direction of the specimen. Before starting the artificial decay,

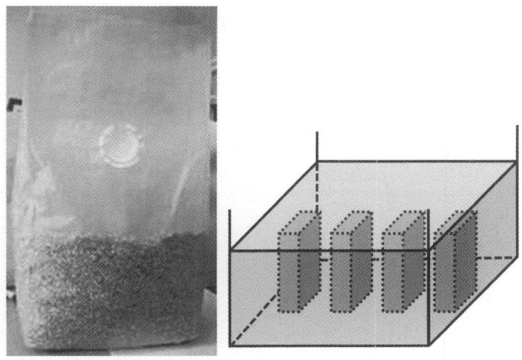


Fig. 1. Film bag filled with vermiculite for fungal exposure.

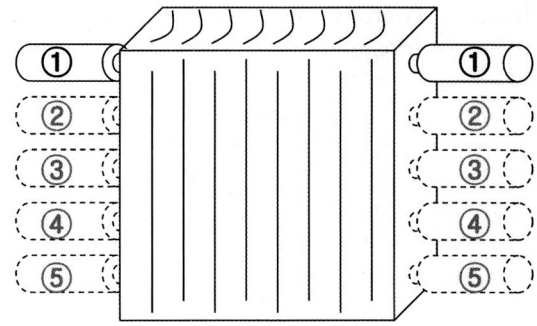


Fig. 2. Schematic diagram of the ultrasonic test.

specimens were oven-dried to 15% of the initial moisture content (MC).

Specimens were divided into four groups made up of combinations of two species of wood and two species of brown-rot fungus (*Fomitopsis palustris*, *Gloeophyllum trabeum*). The combinations were: PF (*P. densiflora* with *F. palustris*), PG (*P. densiflora* with *G. trabeum*), RF (*P. radiata* with *F. palustris*), and RG (*P. radiata* with *G. trabeum*). Artificial decay occurred over 8 weeks, and eight specimens were analyzed every week for every group; consequently, a total of 256 small clear specimens were used (Table 1). In addition, eight non-attacked specimens for each species were used as control specimens.

2.2. Methods

2.2.1. Fungal Exposure

Two species of brown-rot fungus (*F. paulustris* and *G. trabeum*) were used for the artificial fungal exposure. The direct inoculation method proposed by Curling (Curling *et al.*, 2002) was used and modified for whole-section contact with infected vermiculite.

A film bag was filled with 300 g of vermiculite so that the bottom of the bag was covered. Specimens were then placed on the vermiculite and another 400 g was added so that all specimens were completely buried (Fig. 1). Two liters of 1.5% malt extract media was added to adjust the moisture content of the specimens. The bags were then autoclaved at 121°C for 20 minutes.

For each test, the fungi were cultured in 2.5% malt extract media (25 g malt extract, 20 g glucose, 1 g peptone, 1 ℓ distilled water) for a week at 27°C, 120 rpm. The vermiculite was directly inoculated with 20 mℓ mycelia suspension and the cultures were incubated at 27°C. Specimens were aseptically removed from each bag after 1 to 8 weeks of exposure. For each sampling time, specimens were removed from the bags and cleaned to remove any adhering mycelium. The specimens were then oven-dried at 55°C and weighed. Mass loss was determined according to a constant weight at 55°C before and after fungal exposure.

2.2.2. Ultrasonic Test

The ultrasonic Time of Flight (TOF) was measured along the radial direction of the specimens (Fig. 2). Ultrasonic system and method for determining the TOF using an obtained signal uses the protocol developed in a previous study (Kim *et al.*, 2005). Five measurements of each specimen were performed at intervals of 17 mm from the top to the bottom of the specimen (encompassing the total length).

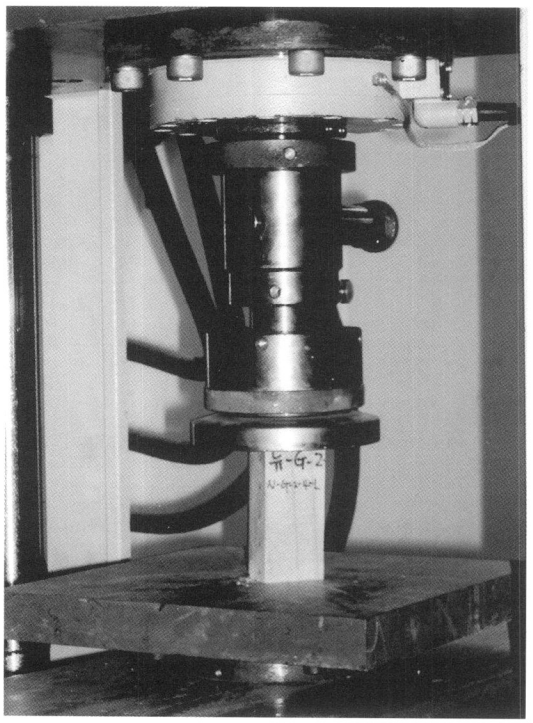


Fig. 3. Specimen under compressive test.

Two bolt-clamped Langevin type (BLT) ultrasonic transducers of 68 kHz in central frequency, made by KAIJO sonic corp. (JAPAN), were used as transmitter and receiver. Sensors were moved together so as to have parallel contact with the specimen (Fig. 2). After the measurement was taken, the TOF values were translated to velocity values with consideration of the transit length (approximately 100 mm). The mean value of five calculated velocities was used as the representative ultrasonic value for each specimen.

2.2.3. Compressive Test

Specimens were cut into two pieces for a compressive test following the ultrasonic test. One piece of each specimen was used for the compressive strength test (Fig. 3), while the other was used for an additional anatomical investigation which is not detailed in this paper. A universal test machine (UTM) was used and the loading velocity was fixed to 0.3 mm/sec. The maximum compressive strength (N/mm^2) and compressive stiffness (MPa) of each specimen were calculated according to the relationship between stress and strain.

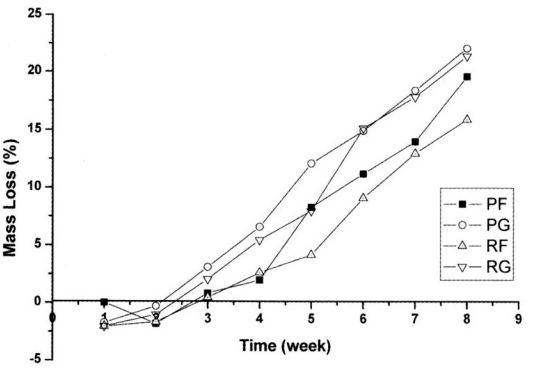


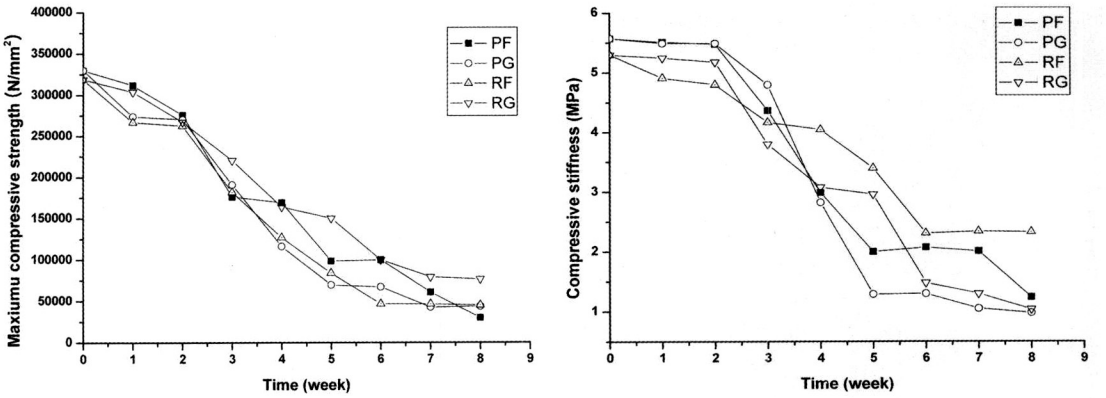
Fig. 4. Relationship between fungal exposure time and decay-induced mass loss for the four groups.

3. RESULTS and DISCUSSIONS

3.1. Mass Loss

The mass loss data, based on the constant weight at 55°C versus the time of decay, is detailed in Fig. 4. Measurable mass loss occurred after approximately 2 weeks for all groups, starting with the PG and followed by the RG, PF, and RF groups, respectively. In the very initial stage of decay (1, 2 weeks), there are minus values of mass loss. This is thought to be caused by remained adhering mycelium which should be removed before weighing. Anyway, it is certain that the measurable mass loss started after 2 weeks after decay.

Following the initial decay-induced mass loss, the mass loss continuously increased after 8 weeks of artificial decay to 22.0%, 21.3%, 19.6%, and 15.9% for the PG, RG, PF and RF groups, respectively. In a previous work by Curling (Curling *et al.*, 2002), about 10% of mass loss oc-



(a) Maximum compressive strength according to fungal exposure time.

(b) Compressive Stiffness according to fungal exposure time.

Fig. 5. Relationship between fungal exposure time and decay-induced maximum compressive strength and compressive stiffness losses for the four groups.

curred after 6 weeks for southern pine specimens with using vermiculite and direct inoculation method (*G. trabeum*). Even the specimen size for determining the mass loss was comparatively larger than the work by Curling (9.5 mm radial, 25 mm tangential and 15 mm longitudinal) almost same or large amount of mass loss occurred in this study. Although there were no significant differences between the four groups, the detected mass loss for the RF group was consistently the lowest.

3.2. Strength Loss

The mechanical properties of maximum compressive strength (MCS) and compressive stiffness versus the fungal exposure time are shown in Fig. 5. The average MCS values for the control specimens (controls) were 33.0 × 10^4 N/mm^2 and 31.9 × 10^4 N/mm^2 for *P. densiflora* and *P. radiata*, respectively. The MCS loss began during the first week of fungal exposure for all four groups and drastically increased (over 30%) after 3 weeks of exposure. The MCS decreased continuously, with final values of 3.0 × 10^4 N/mm^2, 4.4 × 10^4 N/mm^2, 4.5 × 10^4 N/mm^2, and 7.6 × 10^4 N/mm^2 (91%, 87%, 86% and 76% losses) for the PG, RG, PF, and RF groups, respectively, after 8 weeks of exposure (Table 2). However, standard deviation of eight specimens shows large value especially for the value of 7 and 8 weeks of exposure. This is considered to be caused by the eccentric force due to local degradation of the tested specimen.

No significant compressive stiffness losses occurred until 2 weeks after the start of artificial decay (Fig. 5(b)); however, rapid decrease in compressive stiffness values occurred after 3 weeks (about 20% loss). After 8 weeks of fungal exposure, 1.2 MPa, 1.0 MPa, 2.3 MPa, and 1.0 MPa (78%, 82%, 56% and 80% losses) remained in the PG, RG, PF, and RF groups, respectively (Table 2).

No significant changes in compressive stiffness occurred until 2 weeks of artificial decay, and the compressive stiffness continuously increased after three weeks of artificial decay. This tendency is almost identical to that of mass loss detection.

At very early stages of decay, with mass loss values of less than 2.5%, the MCS values were significantly decreased (about 40~50%). After a longer period of decay (up to 5% mass loss), both

Table 2. Decay-induced loss in weight and mechanical properties for four groups according to fungal exposure time

(a) *Pinus densiflora*

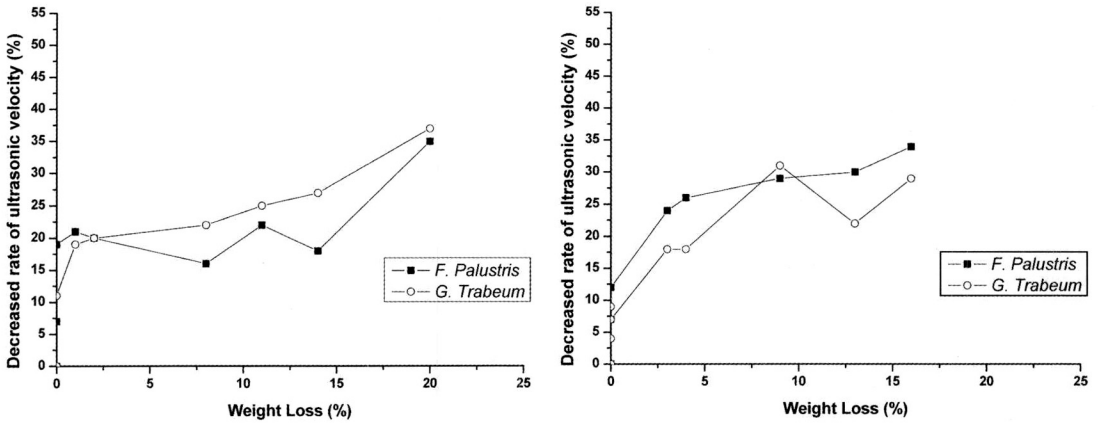
Period (week)	*Fomitopsis palustris*					*Glloeophyllum trabeum*				
	Mass Loss (%)	Maximum compressive strength ($\times 10^4$ N/mm^2)		Compressive stiffness (MPa)		Mass Loss (%)	Maximum compressive strength ($\times 10^4$ N/mm^2)		Compressive stiffness (MPa)	
		Average	Standard deviation	Average	Standard deviation		Average	Standard deviation	Average	Standard deviation
0	0	33.0	7.5	5.6	1.7	0	33.0	7.5	5.6	1.7
1	0.0	31.2	4.5	5.5	0.7	-1.7	27.4	3.9	5.5	1.0
2	-1.8	27.6	4.3	5.5	0.9	-0.3	27.0	7.5	5.5	1.1
3	0.8	17.6	7.0	4.4	1.2	3.1	19.1	5.8	4.8	1.4
4	2.0	16.9	8.7	3.0	1.4	6.6	11.6	4.7	2.8	0.9
5	8.3	9.8	6.3	2.0	0.9	12.1	6.9	2.3	1.3	0.5
6	11.2	10.0	7.5	2.1	1.2	14.9	6.7	1.8	1.3	0.5
7	14.0	6.1	5.1	2.0	1.2	18.4	4.3	5.0	1.1	0.5
8	19.6	3.0	5.3	1.2	1.5	22.0	4.4	6.0	1.0	0.8

(b) *Pinus radiata*

Period (week)	*Fomitopsis palustris*					*Glloeophyllum trabeum*				
	Mass Loss (%)	Maximum compressive strength ($\times 10^4$ N/mm^2)		Compressive Stiffness (MPa)		Mass Loss (%)	Maximum compressive strength ($\times 10^4$ N/mm^2)		Compressive stiffness (MPa)	
		Average	Standard deviation	Average	Standard deviation		Average	Standard deviation	Average	Standard deviation
0	0	31.9	9.5	5.3	1.4	0	31.9	9.5	5.3	1.4
1	-2.1	26.7	5.6	4.9	0.6	-2.0	30.4	5.2	5.3	0.8
2	-1.7	26.3	3.8	4.8	1.2	-1.1	26.7	6.4	5.2	1.2
3	0.5	18.2	2.4	4.2	0.9	2.1	22.1	5.3	3.8	0.4
4	2.6	12.7	3.2	4.1	0.5	5.5	16.4	7.9	3.1	1.4
5	4.2	8.4	2.4	3.4	0.5	8.0	15.0	5.4	3.0	1.7
6	9.1	4.7	0.6	2.3	0.6	15.1	10.0	2.8	1.5	0.8
7	12.9	4.6	1.3	2.3	0.9	17.8	7.9	3.3	1.3	0.4
8	15.9	4.5	1.5	2.3	0.8	21.3	7.6	3.8	1.0	0.4

※ Strength loss (%) = ($Value_{control\ specimen}$ - $Value_{decayed\ specimen}$) / $Value_{control\ specimen}$ × 100

the MCS and the compressive stiffness decreased drastically. This rate of decay decreased somewhat after the 5% mass loss.



(a) *Pinus densiflora* (b) *Pinus radiata*

Fig. 6. Relationship between mass loss and the decreased rate of ultrasonic velocity.

3.3. Ultrasonic Test

Ultrasonic velocities decreased along with decreasing mass loss (Fig. 6, Table 3). The velocity of the control specimens for *Pinus Densiflora* and *Pinus Radiata* was 828 m/sec and 826 m/sec, respectively. These values were used to calculate the rate at which the velocity decreased.

Ultrasonic velocities decreased over 10% before detectable mass loss occurred after 2 weeks of artificial decay. After this period of decay, the rate at which ultrasonic velocity decreased tapered off, and at the end of the test period (eight weeks of decay), the velocity was about 30% of the original velocity before decay. The average values of decreased rate of ultrasonic velocity were not consistently increased with increased mass loss. This is related to the crack generation of the specimen after initial stage of decay. After generating cracks, ultrasonic velocity is very hard to be determined because of very high attenuation of received ultrasonic signal. From the five measurements, only detected values were used for determining average velocity. So, it was very hard to quantitatively explain the decay after the initial stage only with the ultrasonic velocity.

The decreasing rate of *Pinus densiflora* was larger than that of *Pinus radiata* at the early stages of decay (Fig. 6). This discrepancy is thought to be due to the different annual ring widths of these two species. *Pinus densiflora* has a narrow annual ring width; therefore, the possibility of generating a crack which prohibits penetrating the ultrasound by brown-rot decay is higher. After generating the crack, the ultrasonic velocity shows low and variable values.

This study proved that an ultrasonic test is very sensitive for detecting the early stages of brown-rotted decay. When a mass loss of 20% had occurred, the strength properties were decreased by approximately 80% and the ultrasonic velocity was decreased by approximately 30% from their original values.

4. CONCLUSIONS

F. palustris and *G. trabeum* were directly inoculated onto wood using a modified direct inoculation method to artificially expose two species of wood (*Pinus densiflora* and *Pinus radiata*)

Table 3. Decay-induced loss in weight and ultrasonic velocity for four groups according to fungal exposure time

(a) *Pinus densiflora*

Period (week)	*Fomitopsis palustris*			*Gloeophyllum trabeum*		
	Mass Loss (%)	Ultrasonic Velocity		Mass Loss (%)	Ultrasonic Velocity	
		(m/sec)	Decreasing rate (%)		(m/sec)	Decreasing rate (%)
0	0	828	0	0	828	0
1	0.0	773	7	-1.7	735	11
2	-1.8	668	19	-0.3	734	11
3	0.8	658	21	3.1	669	19
4	2.0	666	20	6.6	660	20
5	8.3	693	16	12.1	646	22
6	11.2	647	22	14.9	619	25
7	14.0	676	18	18.4	603	27
8	19.6	542	35	22.0	524	37

(b) *Pinus radiata*

Period (week)	*Fomitopsis palustris*			*Gloeophyllum trabeum*		
	Mass Loss (%)	Ultrasonic Velocity		Mass Loss (%)	Ultrasonic Velocity	
		(m/sec)	Decreasing rate (%)		(m/sec)	Decreasing rate (%)
0	0	826	0	0	826	0
1	-2.1	787	5	-2.0	751	9
2	-1.7	804	3	-1.1	794	4
3	0.5	790	4	2.1	767	7
4	2.6	777	6	5.5	678	18
5	4.2	711	14	8.0	676	18
6	9.1	674	18	15.1	566	31
7	12.9	559	32	17.8	644	22
8	15.9	578	30	21.3	585	29

※ Decreasing rate of ultrasonic velocity (%)
= ($V_{aluecontrol\ specimen}$ - $Value_{decayed\ specimen}$) / $Value_{control\ specimen}$ × 100

to fungal decay. The proposed method induced brown-rot decay after 2 weeks. There were no significant differences for any of the parameters measured between species of wood and fungi. The mechanical properties of maximum compressive strength (MCS) and compressive stiffness were used as decay indicators, as was decay-induced mass loss. According to these three decay indicators, the MCS was the most sensitive to decay - approximately six times more sensitive

than mass loss alone - followed by compressive stiffness, which was also highly sensitive.

This study proves that the ultrasonic test is a very sensitive method to detect the very early stages of brown-rot decay. Even after only 1 - 3 weeks of decay, ultrasonic velocity had decreased by more than 10%. From this result, it is clear that it is feasible to use ultrasonic testing to detect fungal decay. This aspect can be considered even more important, because the strength loss is far more severe than the mass loss. The findings from this research will be used as criteria in subsequent studies of brown-rot decay and in additional research, such as computed tomography (CT) image reconstruction.

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