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16. Abstract

The goal of this study was to develop guidelines for bench marking strength and stiffness properties of deteriorated in-service timber piles as a function of the age of the pile and the in-service environment. A parallel research project undertaken to evaluate the load capacity of hollowed timber piles showed a significant reduction in the strength and stiffness of the undamaged portions of the piles. While it is well known that preservative treatment adversely affects the mechanical properties of timber piles, the level of reduction in these properties in the undamaged portion of the piles was significantly higher than expected.

There are two key factors that control strength properties of the seemingly undamaged sections of a given pile in service. They are: (a) the amount of cellulose material in the wood; and (b) the quality of the resin bond between the wood fibers. Piles which appear to be undamaged can exhibit a significant loss in strength due to incipient damage occurring in the piles. This incipient damage is generally due to fungus infestation which is not obvious to the naked eye. If the infestation is widespread the pile could suffer a loss of the cellulose material which can explain the decrease in the strength properties. Also, the leaching of the creosote into the interior of the piles can contribute to some loss in strength.

Small coupons were taken from most of the piles to determine the basic physical and mechanical properties. Several chemical analysis tests were conducted on specimens taken from pile cross-section to determine the level of creosote, lignin, holocellulose, and the degradation of the holocellulose. These tests were conducted in accordance with specified ASTM standards. The mechanical properties obtained from the coupon tests were compared with those obtained from the full-scale pile tests and formula for estimating the pile strength and stiffness from the coupon properties were developed.

The investigation has led to the following conclusions: (1) The pile strength and stiffness are correlated to the strength and stiffness, respectively of the coupons; (2) The mechanical properties of the solid coupons are independent of their location in the pile cross-section; (3) The compressive strength of the coupons was independent of the specific gravity of the coupons; (4) The creosote level in the pile decreased towards the center of the pile; (5) The lignin level remained unchanged across the cross section of the pile indicating that this level is not influenced by either the decay or the service life of the pile; (6) the holocellulose content indicates that degradation occurred in the outer portions of the pile which is most exposed to the environment; and (7) The decay level was unrelated to the compressive strength of the coupons.

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Effect of Incipient Decay on Compressive Strength and Stiffness of Timber Piles

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ABSTRACT

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indicates that degradation occurred in the outer portions of the pile which is most exposed to the environment; and (7) The decay level was unrelated to the compressive strength of the coupons.

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IMPLEMENTATION STATEMENT

The product of this investigation is a methodology for estimating the pile strength and stiffness based on the coupon strength and stiffness, respectively. Given that the degree of hollowness is known, the load capacity of the piles can be computed by utilizing the estimated pile strength value.

The chemical composition of the pile, evaluated by performing chemical analysis of a wood sample from the pile, does not correlate to the strength or stiffness of the pile. For this reason the investigators recommend that the use of a procedure presented in a companion study and based on nail penetration energy for the pile.

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INTRODUCTION

The goal of this study is to develop guidelines for bench marking basic strength and stiffness properties of deteriorated in-service timber piles as a function of the age of the pile and the in-service environment. A parallel research project undertaken to evaluate the load capacity of hollowed timber piles showed a significant reduction in the strength and stiffness of undamaged portions of the piles. While it is well known that preservative treatment adversely affects the mechanical properties of timber piles, the level of reduction in these properties in the undamaged portion of the piles was significantly higher than expected.

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OBJECTIVES OF RESEARCH

The specific objectives of the research efforts are as follows:

(1) To determine the compressive strength and stiffness properties of coupons taken from undamaged portion of piles.

(2) To determine the level of loss of creosote and cellulose in the wood material by chemical analysis.

(3) To determine the loss of lignin by chemical analysis and microscopic examination.

(4) To develop guidelines for bench marking basic strength and stiffness properties as a function of algae and in-service environment.

SCOPE

The Bridge Maintenance Section of DOTD supplied approximately 30 deteriorated timber piles up to ten ft. in length with a representative range of hollowness and splitting (checking). Small coupons were taken from each of the piles to determine the basic material properties. Chemical analyses were performed with samples taken across the width of the piles to determine the levels of creosote, lignin, and holocelluse, and wood decay in the samples. The results obtained from the mechanical tests and chemical analyses are compared to determine if guidelines for bench marking basic strength and stiffness properties are a function of age and environment.

METHODOLOGY

Evaluation of Physical and Mechanical Properties of Coupons

In order to develop an understanding of the influence of the decay parameters on the strength of the pile, it is important to evaluate the basic physical and mechanical properties of coupons extracted from each test pile. Approximately one foot long pieces were cut off at the end of each pile in the process of preparing them for testing (fig. 1). These one foot long pieces were then further cut into pieces labeled 'B' and 'X' (fig. 2). The pieces labeled 'B' were used to obtain the coupons required for mechanical testing and the piece labeled 'X' was used for conducting the chemical analysis. The cut off pieces were used to obtain solid, clear wood coupons. The number of coupons taken from each pile varied from five to sixteen. Since all coupons were taken from the solid wood portion of the cut off sections, only a limited number of coupons could be obtained from the more heavily decayed piles. The location of the coupons in the cross-section of pile No. 17 is shown in figure 3 to illustrate the numbering system used to identify a coupon. Open squares in the cross-section without a number indicate that a coupon could not be obtained from these regions.

Prior to mechanical testing of the coupons, the size and weight of the coupons was recorded. Additionally, the moisture content of the coupons was measured using a moisture meter.

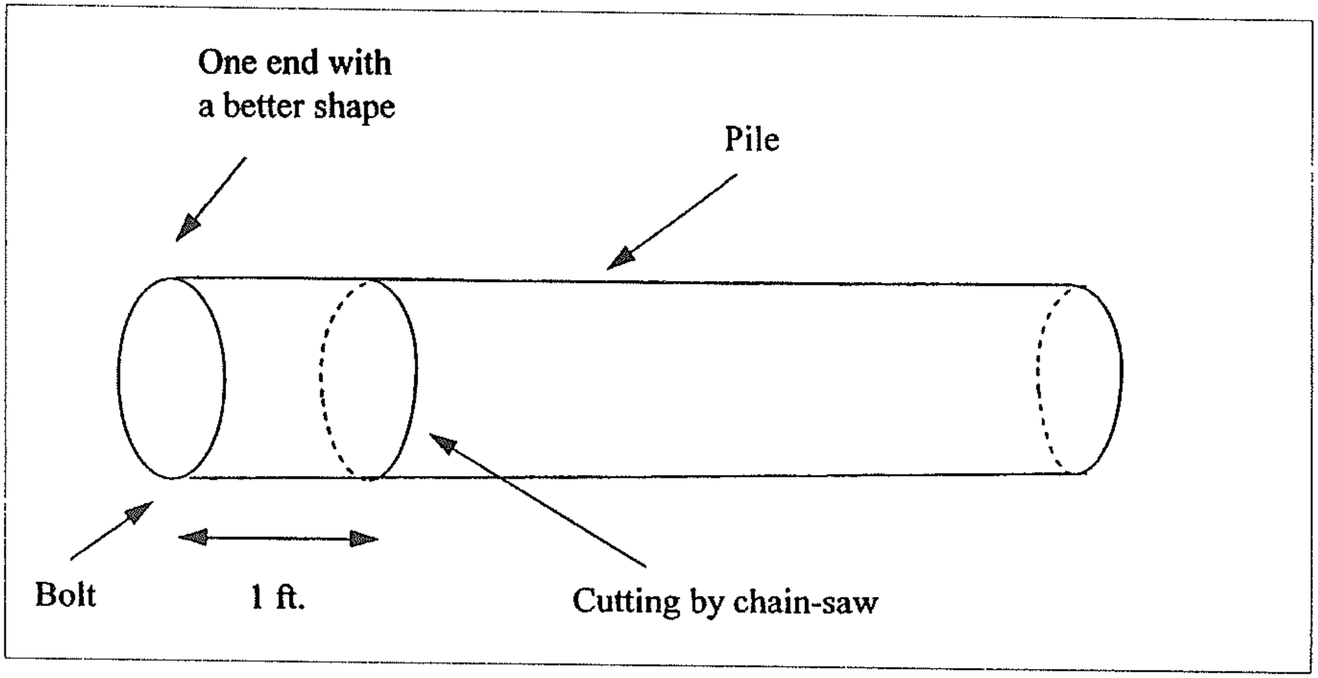

Figure 1
Section of pile used to obtain test coupons

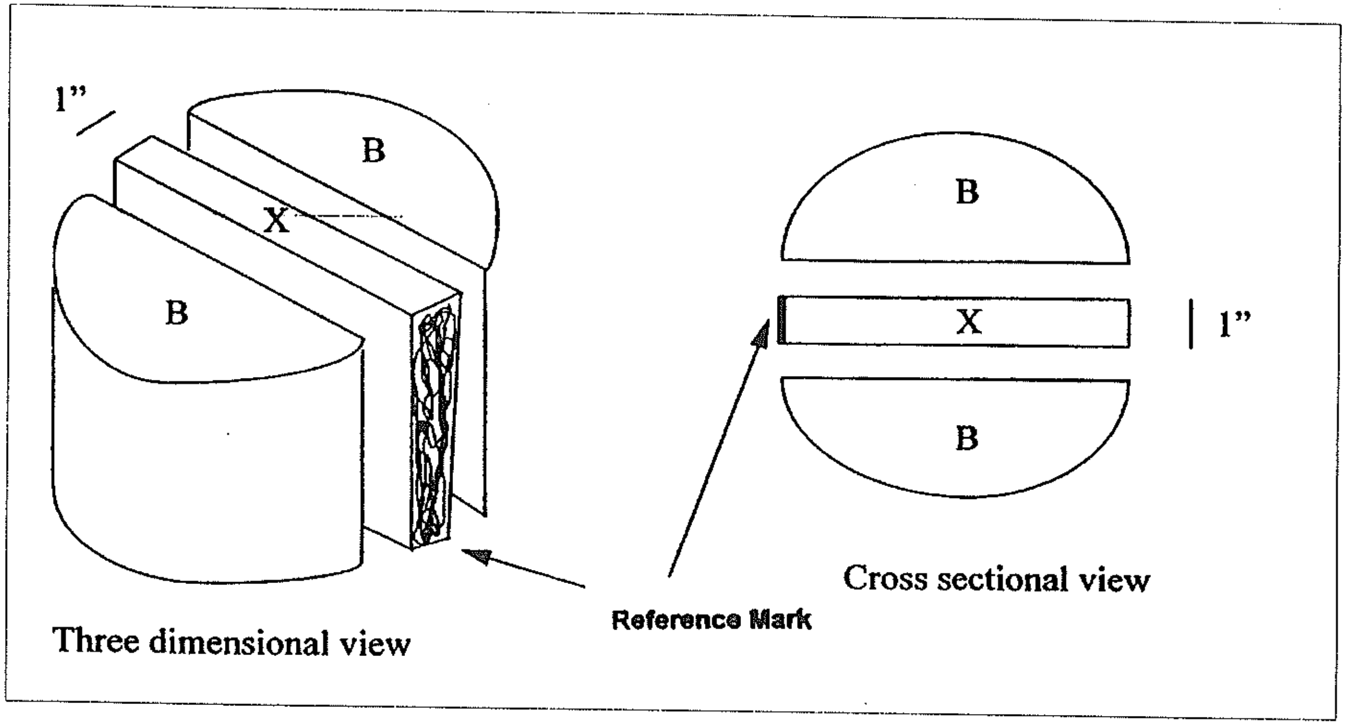

Figure 2
Portions of pile section used for obtaining coupons for mechanical testing and chemical analysis

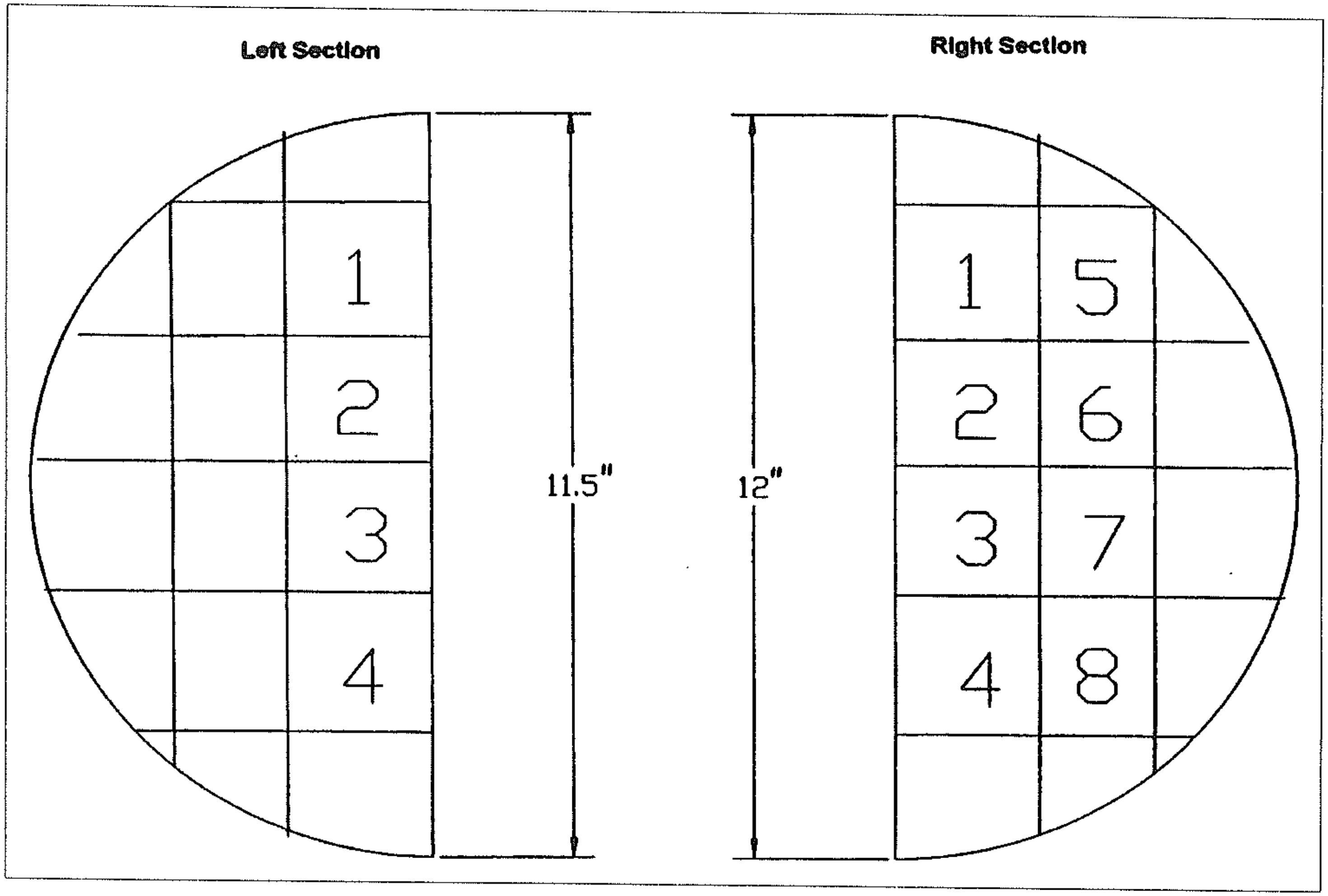

Figure 3
Typical locaton of coupons obtained from solid portion of the pile

While density of the coupons provides an important measure of the mechanical properties, a more accurate indicator of these properties can be obtained by determining the specific gravity of the coupon at zero percent moisture content. This specific gravity, SG_0, can be calculated as follows:

$$SG_0 = \frac{Density\ at\ a\ given\ moisture\ content}{(1 + \frac{Moisture\ Content}{100}) \times 0.0361} \qquad (1)$$

It is pertinent to point out that in the absence of using a moisture meter, the moisture content of the coupons can be computed as follows:

$$Moisture\ Content\ (percent) = \frac{Original\ Weight - Weight\ Oven\ Dry}{Weight\ Oven\ Dry} \times 100\% \qquad (2)$$

The compressive strength (parallel to grain) and modulus of elasticity of the coupons taken from the undecayed portion of the pile section were determined in accordance with the test specified in ASTM D-695. As mentioned earlier, a minimum of five coupons were taken from each pile, but more were taken if enough solid material was available. The test coupons were loaded with a head movement rate of 0.05 in./minute (1.27 mm/minute) until the peak load had been reached. After the peak load had been reached, the machine head movement was stopped for a minute or so to view the relaxation. The testing was resumed with a head movement rate of 0.2 in./minute (5 mm/min.) Until the coupons failed. The modulus of elasticity parallel to grain was obtained from the experimental load versus deformation data.

Results of mechanical properties tests

A variable number of coupons were taken from the test piles to determine the clear wood ultimate compression stress. The results are shown in table 1. Excluding pile 9 coupons, the average ultimate stress is 2,816 psi (19,403 kPa). The coupons from Pile 9 averaged over 60 percent higher values. It is apparent that even the "solid" wood in the piles have deteriorated with time.

With the exception of a few piles, the modulus of elasticity (MOE) of the coupons was representative of the pile modulus of elasticity. The coupon average MOE and the corresponding pile MOE values are shown in table 2 for piles 14 through 32. The coupon data for piles 1 through 13 was not available for this study.

Table 1
Results of coupon compression tests

Pile Number	Number of Coupons	Avg. Ult. Comp. Stress (psi)
3	2	1769
4	4	3225
5	2	2728
6	3	3003
7	3	3097
8	6	2824
9	6	4679
10	3	4321
11	4	7547
12	5	4687
13	5	2201
14	11	4288
15	9	3222
16	15	4408
17	12	4699
18	9	4014
19	12	5094
20	11	4093
21	11	4136
23	13	2217
24	5	3150
25	11	2879
26	8	2568
27	11	2587
28	11	2226
29	11	5309
30	9	2169
32	9	228

Table 2

Moduli of elasticity of coupons and piles (Piles 14-32)

Pile Number	Coupon Avg. MOE (psi)	Pile MOE (psi)
14	618,914	746,374
15	519,027	796,414
16	636,910	952,009
17	704,135	612,984
18	544,327	894,835
19	680,268	957,576
20	651,620	900,139
21	633,766	756,151
23	302,839	209,986
24	312,491	334,324
25	479,026	111,062
26	384,444	371,030
27	442,889	436,920
28	381,597	425,790
29	713,022	844,440
30	380,603	437,177
32	328,017	477,13

Chemical analysis

Samples for performing the chemical analysis were obtained from 17 deteriorated wood piles which were furnished for full scale testing during the second phase of a parallel project. The samples were taken from the pieces cut off at the end of the piles as discussed earlier and shown in figures 1 and 2. The section labeled 'X' in figure 2 was about an inch thick and was cut longitudinally using a band-saw into seven specimens of equal width of 1.5 inches as shown in figure 4. The seven specimens are numbered as shown in Fig. 4, and this numbering system is used refer to the specimens in tables presented in later sections of this report. It is important to note that specimens 1 and 7 are the exterior specimens, 2 and 6 are the first interior specimens, 3 and 5 are the interior specimens, and 4 is from the center/pith of the pile. The chemical analysis of the wood samples was performed to establish the level of creosote, lignin, homocellusoe and degradation in the pile cross-section. The flow chart adopted for completing the chemical analysis of the wood samples is shown in figure 5.

Each of the specimens was ground to small wood particles using a Wiley mill with a 40-mesh screen, then air-dried. The air-dried particles were utilized to perform the various chemical analysis tests. All the analyses were done in duplicate in accordance with the ASTM Standard.

Solubility in alcohol-benzene (1 to 2 volume proportion) (ASTM D 1107-57) was first performed to remove the residual creosote and the oil- and water-soluble extractives, leaving the non-extractable substances (lignin, hemicellulose, and cellulose) behind. This test provided a measure of the level of creosote and other solubles in the wood.

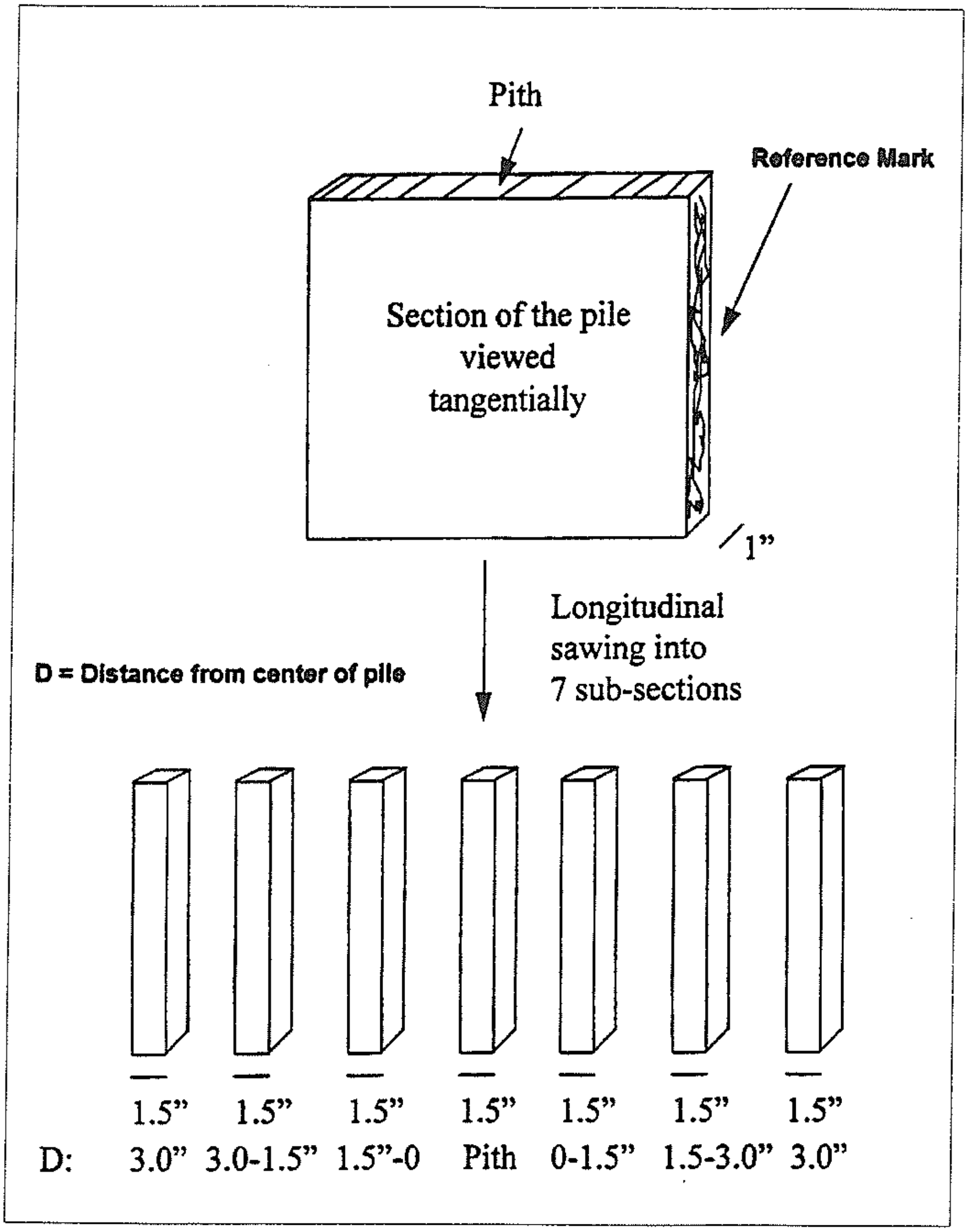

Figure 4
Location of specimens for chemical analysis

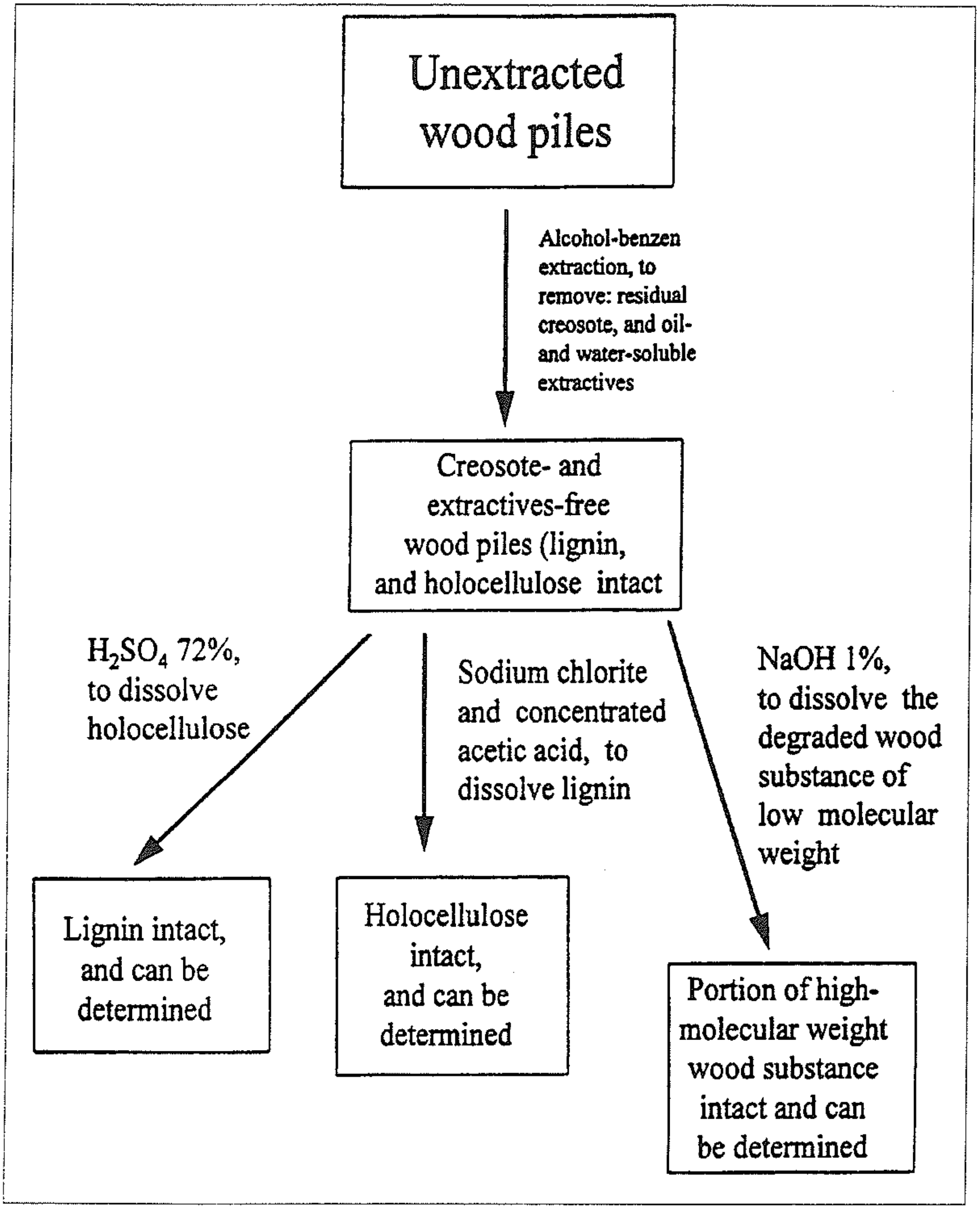

Figure 5
A flow chart for chemical analysis of wood specimens

Results of chemical analysis

The solubility of the specimens in alchohol-benzene, which indicates the amount of residual creosote and oil-soluble (non-polar), and water-soluble (polar) extractives, is presented in table 3, and was, to some extent, specific for certain pile samples.

Table 3
Creosote content indicated by solubility in alcohol-benzene

Pile Number	Creosote Content (%)						
	Coupon No. in Pile Section 'X'						
	1	2	3	4 (Pith)	5	6	7
14	37.5	14.7	14.6	20.8	13.9	12.3	30.0
15	35.0	16.0	4.7	19.5	4.5	14.2	28.4
16	32.5	8.3	4.9	16.1	4.2	8.7	29.4
17	32.5	9.9	6.0	17.8	4.5	16.2	44.8
18	39.0	19.8	3.3	14.5	4.5	18.7	41.4
19	23.1	19.7	11.0	14.3	11.0	16.6	25.1
20	37.8	9.1	4.7	12.1	5.4	14.8	44.9
21	30.1	11.5	6.8	18.4	8.2	15.9	42.6
23	36.8	12.1	6.2	14.2	8.1	13.1	37.4
24	24.0	13.5	5.1	16.9	6.2	14.1	25.1
25	28.4	19.9	6.0	16.2	6.1	17.2	26.1
26	32.1	102	8.8	19.3	9.2	13.2	34.4
27	22.5	18.70	9.9	15.2	10.1	16.6	24.1
28	24.1	12.1	6.7	13.2	6.0	14.1	25.1
29	24.1	12.1	6.7	13.2	6.0	14.1	25.1
30	21.2	9.7	4.8	17.1	4.0	10.1	20.8
32	36.7	14.1	8.1	14.1	6.3	16.2	42.2

DISCUSSION OF RESULTS

The coupon tests yielded some interesting, though expected, results. The average compressive strength of the coupons taken form a pile was reflective of the condition of the wood material in the pile. Hence, the lower the strength value, the lower the pile strength. A plot of coupon stress at failure versus the pile stress at failure is shown in figure 6 and shows a good correlation between these two properties. If the average coupon failure compressive stress is known, the pile net failure compressive stress can be estimated as follows:

$$f_n = 1.12 f_n^c - 1976 \qquad (3)$$

where: f_n = pile net failure compressive stress
f_n^c = coupon failure compressive stress

A plot of the coupon failure stress versus the specific gravity, SG_0, shown in figure 7 did not have a good correlation. For this reason, the use of specific gravity as a measure of the compressive strength of the piles was ruled out. A plot of the coupon modulus of elasticity versus the pile modulus of elasticity is shown in figure 8 and clearly shows good correlation between these two properties. The modulus of elasticity of the pile can be estimated from the coupon modulus of elasticity applying the following relationship:

$$E_{pile} = 2.37 E_{coupon} - 608900 \qquad (4)$$

where: E_{pile} = modlulus of elasticity of pile
E_{coupon} = modulus of elasticity of coupon

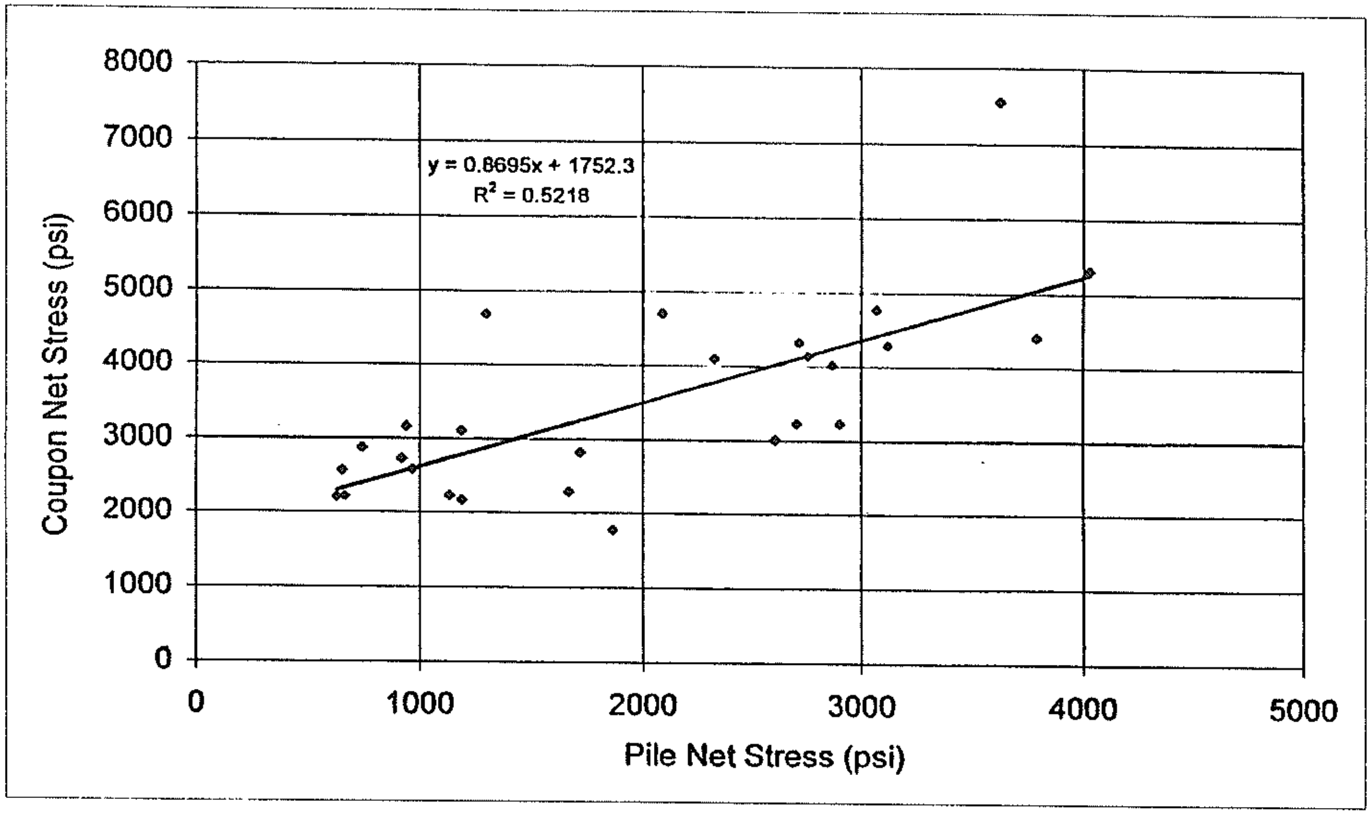

Figure 6
Coupon failure compressve stress vs. pile net failure compressive stress

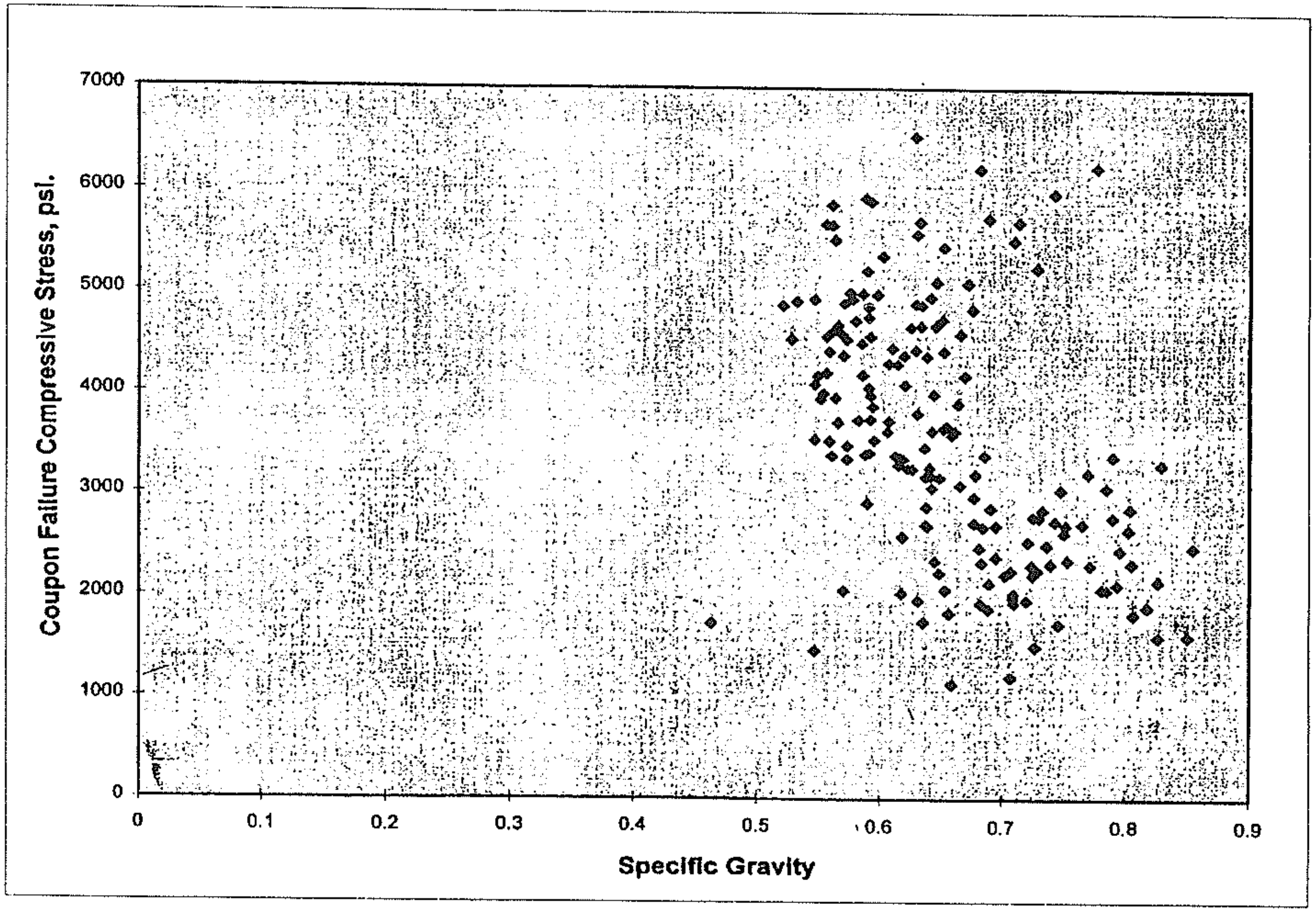

Figure 7
Coupon failure compressive stress vs. specific gravity

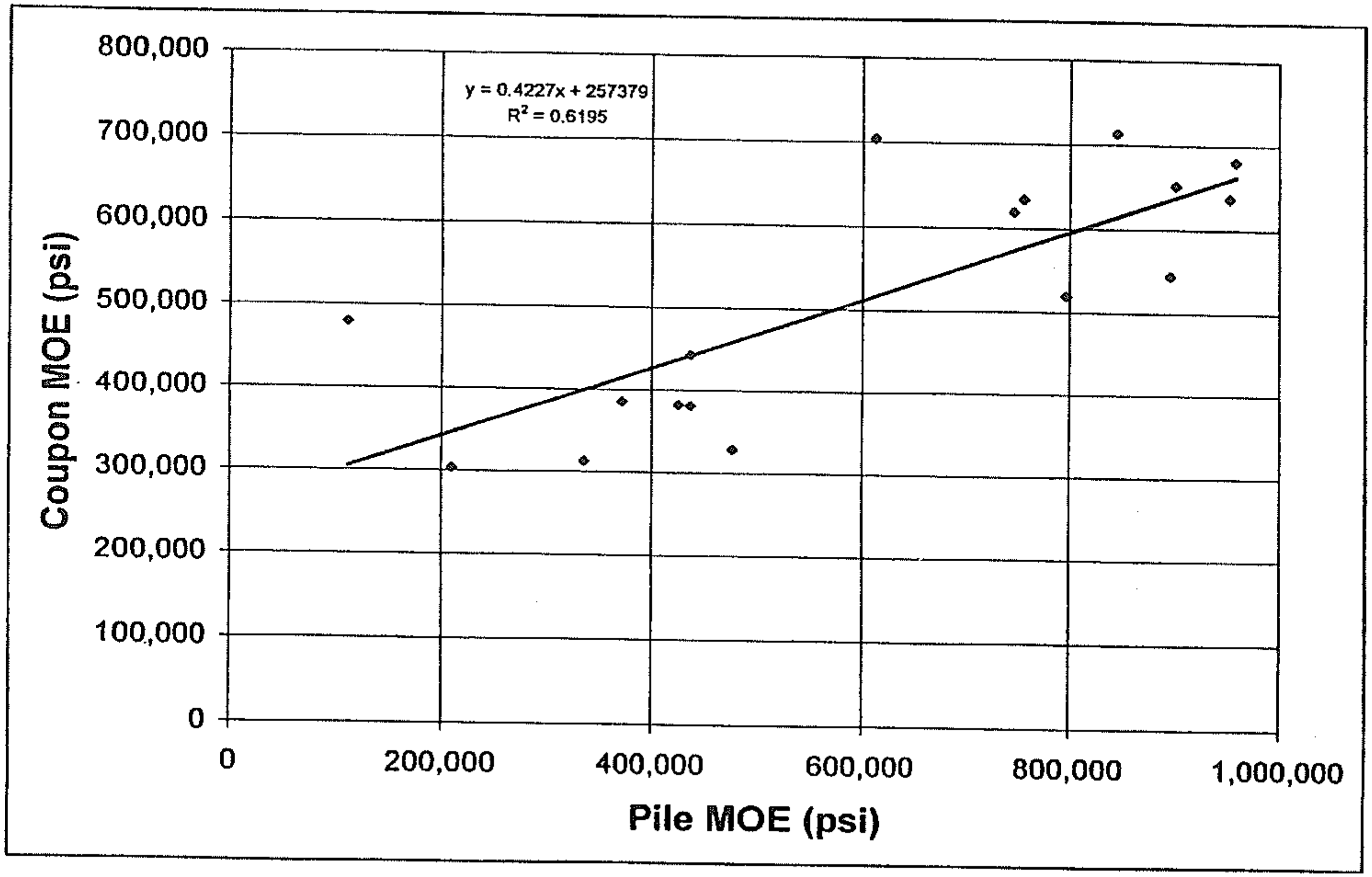

Figure 8
Coupon MOE vs. pile MOE

Based on the chemical analysis, the duration of service and surrounding conditions might affect the residual creosote and other extractable materials in the piles. However, the distribution of alcohol-benzene solubility showed similar patterns among all the piles. The outer portions tended to have the highest solubility. The solubility decreased toward the pith, but it increased in the pith.

The high solubility in the outer portions was due to the higher residual creosote content in the exterior/sapwood zone of the pile. During pressure treatment the outer portion of the piles absorbs higher levels of preservative than the interior. The pith region, which consists mostly of primary tissue (unlignified parenchymatous thin-wall cells), has large amounts of polar substances (Tsoumi 1991) which result in high alcohol-benzene solubility. The high solubility of specimen No. 4 in all the piles is not due to creosote content.

The lignin content in the specimens was determined by ASTM D1106-56 and the results of this analysis are presented in table 4. The results presented show no significant changes in the lignin from the surface of the pile to the pith region. The lignin content, which ranged from 27 to 31 percent, is typical for softwood species. These results clearly indicate that the lignin in the deteriorated piles remained unchanged over the service life period. The holocellulose content in the specimens was determined by ASTM D1104-56 and the results are presented in table 5. The analysis of holocellulose indicated that the content in the outer portions was slightly lower than in the inner portions and in the pith. This trend revealed that the polysaccharide fractions of the wood cell wall underwent significant degradation during service. Though the overall holocellulose contents (64 - 75 percent) were above the normal range of 40 - 45 percent for cellulose content in most wood species, degradation occurred to the carbohydrates of the cell wall with low molecular weight fractions or shorter polymer chains (hemicellulose), while those with higher MW fractions or longer polymer chains (cellulose) were presumably still intact.

The level of wood decay was determined by evaluating the solubility of the specimens in 1 percent NaOH. The results of this analysis are presented in table 6. Degradation of the holocellulose, with lower molecular weight, was confirmed by the higher solubility in one-percent NaOH at the outer portions, as compared to the inner portions. On the other hand, greater solubility of the pith in NaOH was again due to the higher content of parenchymatous tissue which has thin-walled cells. These results clearly show that higher level of degradation occurs in the outer portion of the pile than the inner portions.

The average ultimate compressive stress of the exterior coupons - those extracted from the outer portions of the pile - and the solubility in 1 percent NaOH of the wood in the corresponding outer portions of the pile are presented in table 7 and graphically illustrated in figure 9, The plot in figure 9 clearly shows that the ultimate compressive stress of the sound portions of the pile is not influenced by the level of degradation of the holocellulose and as such the decay level cannot be used as a predictor of the loss in pile strength.

Table 4

Lignin content determined by solubility in H_2SO_4

Pile Number	Lignin (%) Coupon No. in Pile Section 'X'						
	1	2	3	4 (Pith)	5	6	7
14	31.5	30.3	29.3	28.0	31.7	29.4	30.1
15	31.3	30.7	31.5	30.4	29.6	28.4	28.8
16	31.3	30.0	30.2	32.1	29.1	28.3	29.6
17	29.0	28.0	29.4	29.7	28.1	28.5	29.5
18	30.6	31.3	31.1	29.1	29.5	31.1	30.4
19	30.8	29.5	30.9	31.8	30.8	29.9	30.2
20	27.7	27.5	28.0	30.7	30.2	29.9	30.6
21	30.3	29.0	28.9	30.7	30.2	29.9	30.6
23	28.1	27.9	27.9	28.5	27.9	28.1	30.1
24	28.3	28.1	27.7	28.3	28.1	27.4	28.9
25	29.0	28.8	29.0	29.2	28.4	27.9	28.1
26	29.1	28.9	30.1	30.6	31.1	30.0	30.7
27	29.8	28.9	30.1	31.0	30.6	29.9	31.1
28	30.1	30.0	30.1	31.7	30.8	30.0	30.2
29	30.1	30.0	30.1	31.7	30.8	30.0	30.2
30	29.1	29.7	30.1	29.0	29.4	28.9	30.1
32	28.2	27.9	28.0	29.1	28.7	28.0	29.2

Table 5
Holocellulose Content

Pile Number	Holocellulose (%)						
	Coupon No. in Pile Section 'X'						
	1	2	3	4 (Pith)	5	6	7
14	64.6	71.4	75.9	74.4	69.7	67.2	64.2
15	65.2	67.2	74.5	70.4	76.0	68.0	63.9
16	67.6	75.5	76.2	67.4	74.2	70.4	67.6
17	65.1	70.2	73.9	72.8	72.4	77.0	61.0
18	67.7	76.4	75.4	74.6	74.7	75.8	66.0
19	68.2	75.6	71.1	70.7	71.6	71.1	67.4
20	64.8	76.9	77.8	72.4	75.6	78.1	70.8
21	67.9	72.2	73.0	75.0	73.6	69.9	66.3
23	68.8	74.1	75.3	73.8	74.1	74.9	70.9
24	66.2	68.2	74.2	73.8	74.3	67.6	65.9
25	70.1	71.2	73.2	72.2	73.4	69.7	68.1
26	67.2	73.1	74.1	71.1	73.4	68.4	65.2
27	65.7	74.2	73.1	72.3	71.9	69.9	65.3
28	64.5	71.4	75.2	69.1	67.1	65.1	64.2
30	65.3	74.2	74.1	74.0	72.6	70.2	64.2
32	68.8	75.9	77.1	74.1	75.1	76.1	69.1

Table 6
Degradation of Holocellulose measured by solubility in 1% NaOH

Pile Number	Holocellulose (%)						
	Coupon No. in Pile Section 'X'						
	1	2	3	4 (Pith)	5	6	7
14	21.5	14.4	14.1	20.4	15.1	17.4	23.3
15	25.6	22.2	11.1	19.7	9.8	19.3	24.0
16	16.5	12.5	11.5	17.7	12.3	14.6	17.8
17	17.2	13.2	13.2	20.9	16.2	18.6	21.5
18	25.4	15.6	11.1	15.8	13.5	14.5	23.1
19	18.3	13.3	11.0	19.6	12.5	15.5	17.1
20	24.5	18.2	12.6	18.8	14.4	14.6	22.6
21	19.5	15.8	14.6	18.7	15.7	18.2	21.0
23	23.2	19.1	10.9	17.2	12.7	17.6	21.9
24	23.8	20.3	11.2	18.5	12.1	19.4	22.4
25	16.1	14.2	14.1	19.2	16.1	17.2	19.2
26	20.1	16.1	13.8	19.2	15.7	18.6	22.1
27	20.2	13.4	10.0	17.7	12.4	15.7	18.2
28	18.1	14.0	10.9	18.8	12.2	16.0	17.0
29	18.1	14.0	10.9	18.8	12.2	16.0	17.0
30	17.1	13.1	10.2	16.2	9.3	14.2	18.9
32	24.2	19.2	11.7	19.1	13.2	15.7	20.6

Table 7
Exterior coupon failure stress and degradation of holocellulose

Pile Number	Degradation of Holocellulose in Outer Portion of the Pile (%)	Average Ultimate Compressive Stress of Exterior Coupons (psi)
14	22.4	4156
15	24.8	3249
16	17.15	4547
17	19.35	4509
18	24.25	4354
19	17.7	4913
20	23.55	4272
21	20.25	3738
23	22.55	2343
25	17.65	2771
26	21.1	2627
27	19.2	2660
28	17.55	2449
29	17.55	5827
30	18	2186
32	22.4	2287

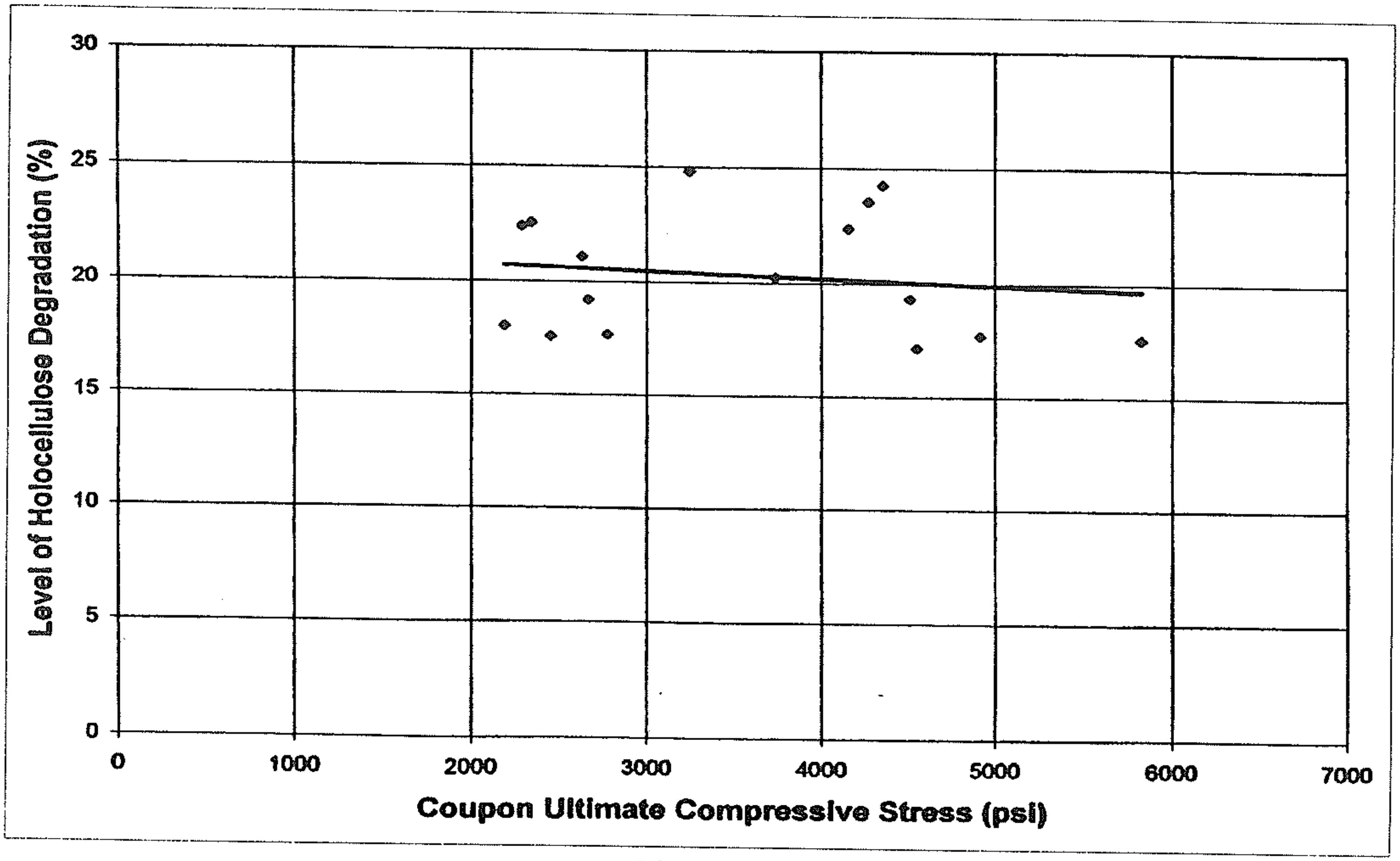

Figure 9
Coupon failure compress stress vs. degradation level of holocellulose

CONCLUSIONS

The results of this study clearly show that the pile strength and stiffness are correlated to the compressive strength and stiffness, respectively, of the coupons taken from the solid portion of the pile. Procedures for estimating the pile strength and stiffness as a function of the coupon properties are presented. The coupon compressive strength was found to be independent of the specific gravity.

Greater residual content in the outer portion of the weathered piles was responsible for the higher alcohol-benzene solubility. On the other hand, high alcohol-benzene solubility of the pith portion was due to greater content of polar extractives.

The lignin level remained unchanged across the cross-section of the pile indicating that this is not influenced by either the decay or the service life of the pile. Also, the level of lignin was comparable to that found in southern pine.

Slightly lower holocellulose content in the outer portions, compared to the inner portions of the piles, indicated that degradation occurred to cell wall carbohydrates with lower molecular weight.

The normal levels of lignin and cellulose (homocellulose with higher MW) present in all sections of the deteriorated pile explain why the mechanical properties of the coupons taken from different sections of the pile are not significantly different. For this reason the use of chemical analysis results to predict mechanical properties of a deteriorated pile is not appropriate.

RECOMMENDATIONS

Based on this study, it is recommended that a chemical analysis cannot be used to predict the mechanical properties of deteriorated piles.

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