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UNITED STATES DEPARTMENT OF THE INTERIOR

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	min	minute
h	hour	pct	percent
in	inch	psi	pound per square inch
in/min	inch per minute	st	short ton
lb	pound		

EFFECT OF LOAD RATE ON WOOD CRIB BEHAVIOR

By Thomas M. Barczak[1] and David E. Schwemmer[2]

ABSTRACT

The effect of load rate on the load-carrying capabilities of wood cribs is investigated in this Bureau of Mines study. The modulus of deformation (stiffness) of wood crib blocks has been shown to increase with increases in rates of load application, causing larger load reactions for increases in convergence rates. Since wood cribs are tested in the laboratory at convergence rates that are orders of magnitude faster than typically would occur underground, wood cribs tested in the laboratory will react larger loads than the same cribs would react underground for the same displacement. Tests conducted in the Bureau's mine roof simulator on green wood crib blocks indicate that the increase in stiffness for increasing load rates diminishes at displacement rates beyond 0.1 in/min, making crib load nearly independent of load rate for rates faster than 0.1 in/min. Seasoned wood specimens were not as consistent in load-rate dependency. Some possible explanations of observed load-rate behavior on wood crib specimens are also postulated in this paper.

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INTRODUCTION

Wood cribbing is used extensively by the mining industry as a means of permanent and expandable roof support. Although the material properties of wood have been well researched, the evaluation of wood crib structures has been limited in scope (1-2).[3] Past research has generally been limited to determinations of the compressive strength of wood cribbing under limited load conditions. These load conditions usually do not include those necessary to design wood structures into the postyield phase. Also, little consideration has been given to parameters that affect the stiffness of the crib system and techniques in which those systems are evaluated in the laboratory. This study considers the effect of load rate on the load-bearing capability of wood crib specimens (crib blocks).

Most materials have some time-dependent properties that affect their behavior. The effects are generally observed as changes in the modulus of deformation (ratio of stress to strain), or the material stiffness (ratio of load to displacement). Cementitious materials show an increase in stiffness for increases in rates of load application. This effect is less pronounced, yet observable, for some viscoplastic materials, such as wood, in the initial linear portion of the load-displacement curve. Since crib structures are tested in the laboratory at faster rates of load application (with respect to reported mine convergence rates) (3), the effect of load rate is an important consideration in the evaluation of wood cribs. Faster load rates utilized in the laboratory result in larger load reactions for a crib tested in the laboratory than the same crib would sustain underground for the same displacement.

The effect of load rate on scaled wood crib supports was investigated by Blight (1). Blight tested model timbers consisting of four block arrangements measuring 3.9 in by 3.9 in. in plan by 2.0 in high, and reported a 40-pct reduction in the deformation modulus of the scaled crib support for decreasing rates of strain. The strain rates investigated by Blight were selected to include the range of rates typical in underground closure (approximately 5×10^{-7} in/min to 5×10^{-2} in/min).

Phang observed a load-rate effect during long-term testing of approximately half-scale, saturated wood crib structures (2). One crib structure was subjected to a sustained 60,000-lb load for 100 days; another was subjected to the 60,000-lb for only 15 min. Since the deformation of the long-term test was larger, it can be concluded that the stiffness of the crib is reduced at slower rates of convergence, which is an indication of a load-rate effect.

The Bureau has expanded upon the work of Blight and Phang by conducting research on full-scale crib blocks in the mine roof simulator (MRS). It is questionable whether the scaled test results can be extrapolated to full-scale crib structures because of the nature of defects in wood specimens. These defects, such as shrinkage cracks, grain size, etc., are relatively large in proportion to crib block and may not be properly evaluated in scaled crib studies. Tests were also conducted at faster load rates (0.05 to 1.0 in/min) than those evaluated by Blight and previous researchers to compare laboratory-tested rates and underground closure rates. This paper presents the results of these tests and suggests future load-rate studies to be conducted on full-scale crib structures as opposed to single-block elements.

A practical application of this research is to enable mine operators to make more valid judgments regarding the selection of wood cribs pursuant to analysis of laboratory test results regarding expected underground behavior. In the broader sense, the long-range objective of the research is to optimize the

[3]Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

utilization and design of these support systems to provide optimum compatibility with the conditions in which they are employed. If the loading conditions (strata behavior) can be identified, a support with the best physical properties (size, weight, etc.) and mechanical properties (stiffness, strength, yieldability, and energy absorption capability) can be designed for that application as a result of this research.

TIME-DEPENDENT BEHAVIOR OF WOOD CRIBBING

Displacement-controlled tests were conducted in the MRS (fig. 1) on full-scale crib blocks 5 in wide by 6 in thick by 30 in long (fig. 2). Oak wood specimens of similar grain pattern were used for all tests. Loading was always applied normal to the grain of the wood in compliance with normal crib construction. Tests were conducted on green (moisture content greater than 30 pct) wood specimens and seasoned (moisture content of 20 to 30 pct) wood specimens. Six rates of load application were investigated in this study: (1) 0.005 in/min, (2) 0.01 in/min, (3) 0.05 in/min, (4) 0.1 in/min, (5) 0.5 in/min, and (6) 1.0 in/min. Five tests were conducted on the green specimens and three tests on the seasoned specimens at each of five rates. Only 41 tests were conducted because seasoned wood specimens were not tested at 0.005 in/min displacement rate, and only one test was conducted on the green specimens at 0.005 in/min. The results of the green wood and seasoned wood tests are documented in appendixes B and C, respectively. Averages for each of the load rates investigated were determined and are used for the documented results. Each crib block was tested to a maximum deflection of 1.2 in, which is well beyond the elastic (linear) behavior of the specimen.

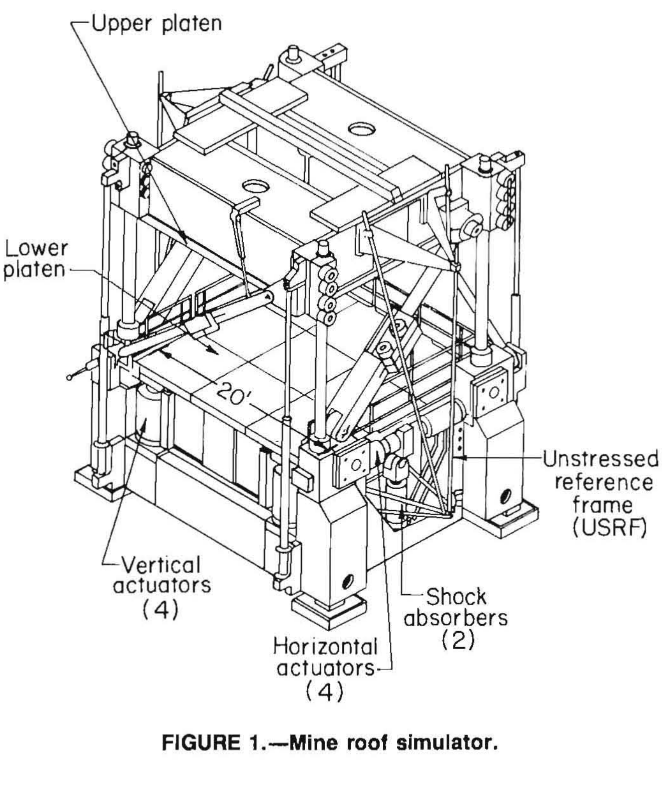

FIGURE 1.—Mine roof simulator.

GREEN WOOD TEST RESULTS

The results of the green wood tests are shown in figures 3 and 4. Figure 3 is a plot of stress (load reacted by the crib divided by the bearing contact area) as a function of loading (displacement) rate. Loads were found to increase with loading rate. Peak loads occurred at 0.05 in/min displacement rate, followed by a slight reduction in load. At load (displacement) rates greater than 0.1 in/min, the load-rate effect on crib response is diminished. At load rates beyond 0.1 in/min, the load sustained by the crib block is nearly the same regardless of the loading rate, making load independent of loading rate for rates beyond 0.1 in/min. This means that cribs tested in laboratory at rates ranging from 0.1 to 1.0 in/min are likely to exhibit nearly the same response in terms of load reaction. Since full-scale crib structures can converge over 2 ft, fast load rates can significantly reduce required test time in laboratory evaluations of these structures.

Below 0.05 in/min displacement rate, the full-scale crib blocks exhibited a

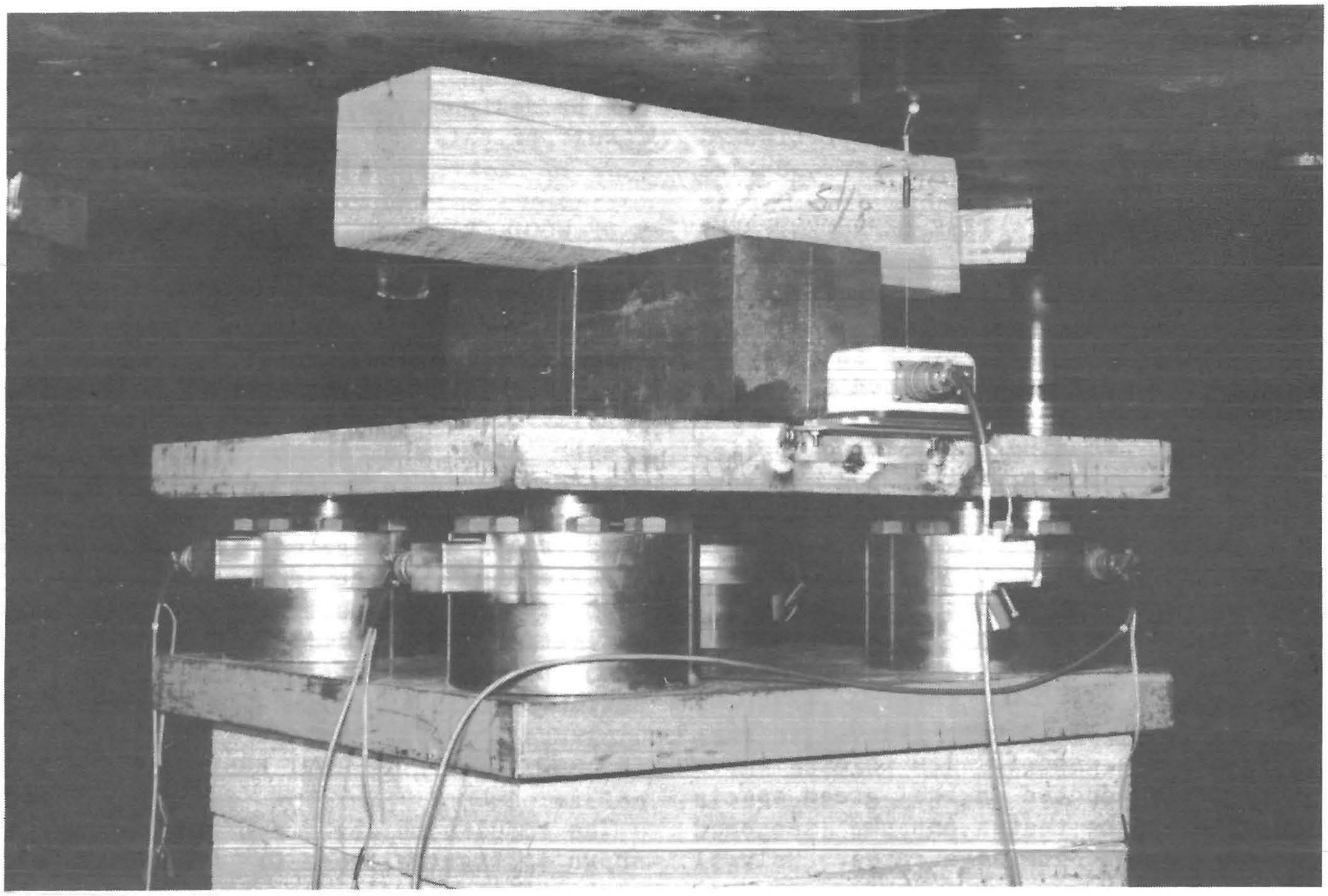

FIGURE 2.—Wood crib test specimens.

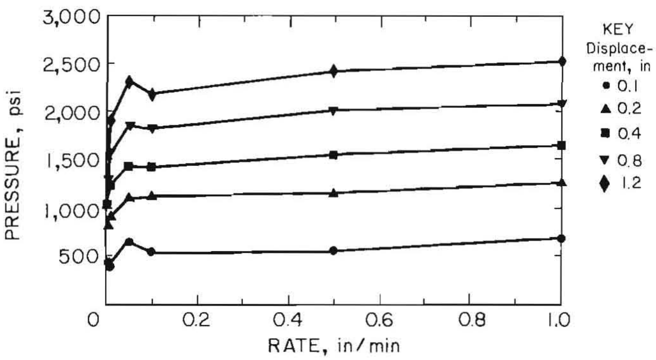

FIGURE 3.—Pressure acting on wood crib specimen as function of load rate.

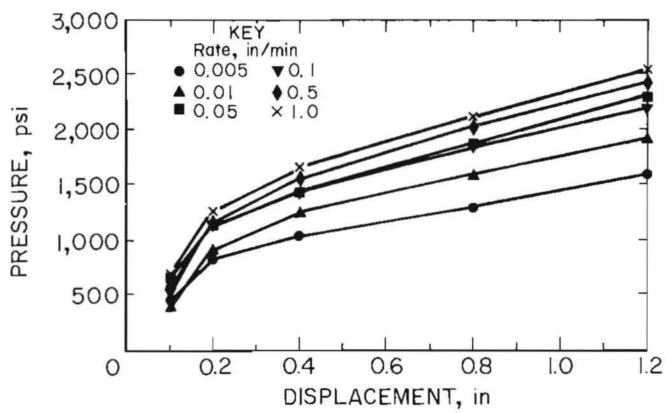

FIGURE 4.—Impact of load rate on stiffness characteristics of wood crib specimens.

similar response to that of the scaled wood crib structures evaluated by Blight (fig. 1); namely, a reduction in load reaction (or stiffness) for corresponding lower rates of load application. There was 29-pct reduction in pressure (averaged over the full 1.2-in displacement range) for crib blocks when the load rate was reduced by a factor of 10 from 0.05 to 0.005 in/min. Rates of closure underground vary depending on geological conditions, strata control practices, and mining operations; but they are reported to be on the order of 0.001 to 0.005 in/min for longwall mining applications (3). Therefore, results of the crib block tests suggest that wood cribs tested in the laboratory at rates beyond 0.05 in/min displacement will sustain about 30 pct more load than the same cribs would sustain underground for the same displacements. The effect of loading rate is consistent across the displacement range investigated because the profile of the pressure versus loading rate plots are similar for each displacement indicated (fig. 3). The rate effect consistently diminished throughout the displacement range at a displacement rate beyond 0.01 in/min, with peak loads at 0.05-in/min displacement rate.

The effect of loading rate on wood crib performance can also be determined by analysis of the stiffness of the crib element, since the load developed in the structure due to applied displacement is a function of the stiffness of the structure. Therefore, if crib load is independent of loading rate, changes in loading rate should not produce changes in the stiffness characteristics of the material. Stiffness is defined as the ratio of load to displacement. The load-displacement relationship for the wood crib elements for each of the six controlled displacement rates is illustrated in figure 4. In the figure, the load displacement curves converge (become closer together) for displacement rates beyond 0.05 in/min, indicating that the stiffness of the crib element is less rate dependent for these rates. For loading rates below 0.05 in/min, there is a well-defined difference in stiffness (as indicated by the spacing between the curves for 0.005, 0.01, and 0.05 in/min). Therefore, analysis of the stiffness of the crib elements also reveals a reduction in the load (support resistance) due to a reduction in stiffness for decreasing rates of convergence for rates below 0.05 in/min. Above 0.05 in/min, the effect of load rate diminishes as the stiffnesses converge to a more constant value.

SEASONED WOOD TEST RESULTS

The results of tests conducted on seasoned wood specimens are shown in figure 5. The effects of loading rate observed for the seasoned wood specimens are not as consistent as those observed for the green wood specimens. For load rates below 0.1 in/min, the following observations are made for the seasoned wood specimens. At the larger displacements (0.8 in and 1.2 in), a rate effect similar to the green wood specimens is suggested, with increased load at increased rates of convergence. For the middle

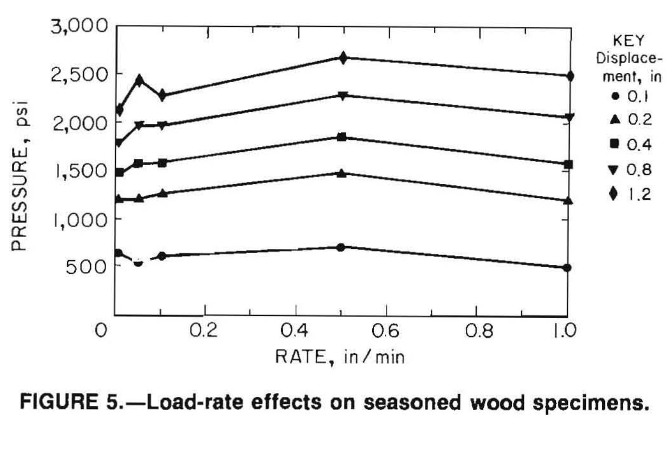

FIGURE 5.—Load-rate effects on seasoned wood specimens.

displacement ranges 0.2 in to 0.8 in, there appears to be little rate effect at all. Below 0.2 in of displacement, the opposite effect is indicated with a slight reduction in load for increased rates of convergence.

Unlike the green wood specimens, seasoned wood specimens exhibit an apparent rate effect for rates above 0.1 in/min. A consistent change in behavior is seen at 0.5 in/min. Loads were found to increase from 0.1 in/min to 0.5 in/min displacement rates, followed by a reduction in load for rates beyond 0.5 in/min.

In summary, load-rate effects for seasoned wood specimens are more inconsistent in the slower displacement ranges (0.01-0.1 in/min) and more pronounced in the faster displacement ranges (above 0.1 in/min) than those observed for green wood specimens. The more general overall trend for seasoned wood specimens is an increase in load with increases in displacement rates (below 0.5 in/min), which is consistent with green wood behavior. Part of this inconsistency may also be attributable to fewer seasoned test specimens.

MECHANICAL DESCRIPTION OF WOOD

As a precursory remark to the following developments, it is instructive to perceive a material on three levels of composition; namely, the macro level (physical observations), the micro level (cell structure), and the atomic level (chemical composition). Analytically, energy principles provide the means to transcend these levels, which is important in light of the philosophy that the behavior of a material on one level is usually investigated by examination of behavior on the next lower level of composition. Therefore, a useful hypothesis of material behavior should have an energy basis, which is motivation for one speculative and unsubstantiated, however plausible the argument presented. A second hypothesis will be presented that is also speculative. To some extent, both (as well as others) of these behavioral responses may be accurate. Advancements of this type are necessary to assist in determining influential material response parameters.

A brief description of wood, first on the macro level and later on a micro level, would include significant processes such as the growth cycle, drying, and environmental conditions (temperature and humidity) that influence the population of voids, defects, and shrinkage cracks and capillaries. These elements affect the behavior of wood specimens. Specifically, the differences in load capacity between green and seasoned wood specimens seem to indicate that increased moisture content (which is environmentally affected) and reduced (shrinkage) crack population results in decreased strength. From a micro-level analysis, wood is describable as a cellular composite connected by intercellular substance, with water existing in the capillary system or in the cell lumens (cavities) or chemically bonded to the cell walls. At this level, seasoned wood is distinguishable from green wood by the loss of cell cavity water.

SOME POSSIBLE EXPLANATIONS OF BEHAVIOR

A qualitative examination of test results is discussed in this section. From the previous development, the first hypothesis proposed speculates that the green wood composition, which is fully saturated internally, acts to arrest or inhibit crack propagation, thereby absorbing this potentially dissipated energy. Phenomena associated with this higher energy capacity in brittle materials (rock, ceramics, concrete) include a reduction in peak load and an increase in ductility (4). Figure 6 depicts the stress-versus-strain profiles for similar sized green and seasoned wood specimens. As anticipated, the green specimens exhibit a lower stress throughout the range of strains tested. It is not possible, however, to verify the peak load or ductility predictions utilizing figure 6, since the tests were terminated before the peak loads were attained. This will

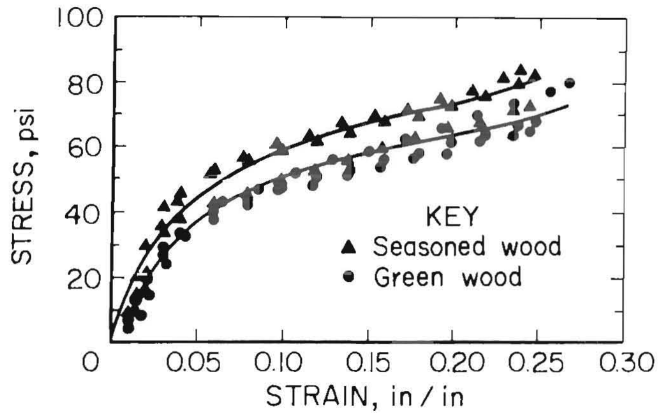

FIGURE 6.—Stress-strain profiles for green and seasoned wood specimens.

be a consideration for future material tests. Determining the effects of material load rate requires analysis of crack propagation (fracture mechanics) at the micro level. Crack propagation is dependent upon, among other things, crack size and available energy to produce and maintain crack growth. The mechanics of crack propagation are not well understood, but it is observed in cementitious materials that an increase in load rate is accompanied by an increase in crack formation and propagation. Assuming that this phenomenon also occurs in wood, an increase in crack growth will occur with an increase in loading rate. Since crack growth releases energy, which enhances strength, load (strength) would be expected to increase with loading rate. Green and seasoned wood specimens exhibited this behavior.

The second hypothesis states that the green wood specimens are more pliable than the seasoned specimens. This may be due to the fiber structure itself, which when wet, provides the wood with added ductility, similar to that of a sponge. Thus the green specimens will behave with more ductility (less stiffness) than the seasoned ones, which is indicated in figure 6.

The cessation of (or diminished) load-rate dependency at certain load rates (0.1 in/min for green wood specimens) suggests a change in material properties at the micro level. This behavior is not commonly observed for other materials and, at this point, is unexplained. Since wood is an organic material, a more basic understanding of its cell structure may provide explanations.

RECOMMENDATIONS FOR FUTURE RESEARCH

This initial investigation was limited to evaluating the effects of load rate on full-size wood crib blocks. Investigation of actual crib supports (structures composed of intersecting layers of crib blocks) was not attempted in this initial study because (1) evaluation of single crib-block elements provided material studies of wood elements without interaction effects between multiple elements, (2) time-dependent studies of wood cribbing are very time consuming. The single crib elements were tested to a maximum displacement of 1.2 in. At a rate of 0.005 in/min (slowest rate tested), 240 min (4 h) is required to produce a deflection of 1.2 in. Assuming each crib element of a crib structure displaces an equal amount, a 16-layer (80-in-high) structure would require 64 h for each test. Therefore, extensive evaluation of full-scale structures was considered impractical for these initial studies.

Now that the effects of load rate have been established for single crib elements, limited investigations of full-scale crib structures should be pursued. Since the crib blocks are the constituents of full-scale crib structures, it is expected that the effect of load rate in full-scale structures will be very similar to that observed during these single-element tests. However, tests need to be conducted to verify this presumption.

Moisture content of the wood was found to significantly influence the effect of load rate on wood specimens. Further studies may be conducted to examine in more detail the micromechanical behavior of wood and moisture content to better determine failure mechanisms. Physical properties of wood have been well researched, but the mechanical properties (fracture mechanics) of wood have received little attention.

Other parameters that might effect load rate should be investigated. Since it is apparent that the composition of the wood specimen is critical to its behavior, other wood types and/or different grain structures (orientations) should be considered.

The material tests on crib blocks presented in this report may be useful in constructing mathematical models of crib structures to evaluate changes in crib geometries and load conditions prior to full-scale testing.

CONCLUSIONS

The studies presented in this report indicate that wood crib systems exhibit time-dependent properties that significantly effect their load-carrying capability in the initial elastic range. For green wood specimens, the effect of increasing the load rate is to increase the stiffness (thus load reaction) of the green wood specimens at displacement rates below 0.05-0.1 in/min. Above these displacement rates, load reactions of the green wood specimens appear to be largely independent of loading rate.

This is significant for two reasons. First, since crib structures are typically tested in the laboratory at rates greater than 0.1 in/min, the same crib structure would sustain significantly lower loads (approximately 30 pct) in an underground environment where the loading rate (convergence) is likely to be orders of magnitude slower. Second, laboratory test time can be reduced considerably by testing at rates faster than 0.1 in/min without introducing additional rate effects.

Seasoned wood specimens exhibited load-rate behavior less consistent than that of the green wood specimens. Like the green wood specimens, the more general trend is increased load reactions for increased loading rates, which implies that laboratory tested cribs will experience more load than underground cribs for the same displacement. However, unlike the green wood specimens, there does not appear to be a well-defined displacement (load) rate range for which load is independent of loading rate.

Explanations of load-rate behavior of wood materials are speculative at this time. Two hypothesis are proposed: (1) Moisture acts to absorb crack-propagation energy, resulting in decreased strength, and (2) wood specimens with higher moisture content exhibit more plastic deformation simply because the material is more pliable than dryer specimens. Additional studies would be helpful in evaluating the micromechanical behavior of wood before more conclusive explanations of behavior can be postulated. Classical fracture mechanics have not been successfully applied to the viscoplastic behavior of materials such as wood.

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APPENDIX A.--DESCRIPTION OF MINE ROOF SIMULATOR

The mine roof simulator (MRS) is a large hydraulic press (see figure 1 of text) designed to simulate the loading of full-scale underground mine roof supports. The MRS is unique in its ability to apply a vertical and a horizontal force simultaneously.

The vertical and horizontal axes can be programmed to operate in either force or displacement control. This capability permits tests, such as true friction-free controlled loading of shields, which cannot be accomplished in uniaxial test machines since the shield reacts a horizontal load to vertical roof convergence. Friction-free tests of this nature can be accomplished in the MRS by allowing the platen to float in the horizontal axis by commanding a zero horizontal load condition. Likewise, the MRS can apply controlled horizontal loading to a shield support, whereas uniaxial test machines can only apply vertical loading with no control over horizontal load reactions and no capability to provide a specified horizontal load to the structure. The controlled displacement capability allows determination of structure stiffness, which is essential to understanding the load-displacement characteristics of the structure.

The machine incorporates 20-ft-square platens with a 16-ft vertical opening to enable full-scale testing of longwall roof-support structures. Capacity of the simulator is 1,500 st of vertical force and 800 st of horizontal force with controlled displacement ranges of 24 in vertically and 16 in horizontally. Load and displacement control is provided in four ranges operating under a 12-bit analog-to-digital closed-loop control network, providing a load control capability of better than 0.1 kips (1,000 lb) and displacement control capability of better than 0.001 in. in the smallest load-to-displacement range.

Machine control and data acquisition is achieved with a DEC 11/34 computer. Eighty-eight channels of test-article transducer conditioning are provided. Data acquisition is interfaced with the control network so machine behavior can be controlled by response of the test-article instrumentation. For example, tests can be terminated or held when strain values reach a designated level in specified areas of a support structure. High-speed data acquisition is available with a separate (DEC 11/23) computer at a rate of 300 samples per second. An X-Y-Y recorder provides real-time plotting of three data channels, and all data are stored on computer disks for subsequent processing and analysis.

APPENDIX B.---PRESSURES FOR GREEN WOOD CRIB SPECIMENS AT FIVE DESIGNATED DISPLACEMENTS

Load rate, in/min	Designated displacement--				
	0.1 in	0.2 in	0.4 in	0.8 in	1.2 in
0.005: Test 1	457	835	1,041	1,289	1,590
0.01:					
Test 2	440	1,018	1,400	1,740	2,115
Test 3	440	930	1,200	1,460	1,740
Test 4	605	930	1,190	1,540	1,820
Test 5	195	814	1,160	1,470	1,770
Test 6	420	913	1,300	1,720	2,150
Av	420	921	1,250	1,586	1,919
Std dev	146	72	61	135	197
0.05:					
Test 7	760	1,120	1,450	1,870	2,240
Test 8	656	1,040	1,300	1,650	1,982
Test 9	650	1,420	1,960	2,795	3,750
Test 10	630	1,050	1,320	1,580	1,890
Test 11	618	960	1,180	1,400	1,700
Av	662	1,118	1,442	1,860	2,312
Std dev	56	178	304	549	826
0.10:					
Test 12	650	1,390	1,740	2,100	2,400
Test 13	630	1,150	1,430	1,815	2,190
Test 14	430	1,040	1,330	1,745	2,140
Test 15	530	1,060	1,400	1,910	2,310
Test 16	550	1,015	1,260	1,610	1,923
Av	558	1,131	1,432	1,836	2,192
Std dev	88	153	184	183	181
0.50:					
Test 17	220	1,000	1,525	1,980	2,330
Test 18	850	1,220	1,550	2,010	2,355
Test 19	350	1,200	1,730	2,330	2,840
Test 20	660	1,180	1,460	1,840	2,235
Test 21	760	1,200	1,520	1,955	2,330
Av	568	1,160	1,557	2,023	2,418
std dev	270	90	102	183	181
1.00:					
Test 22	780	1,130	1,380	1,750	2,220
Test 23	330	1,350	1,830	2,350	2,890
Test 24	660	1,200	1,530	1,960	2,355
Test 25	1,050	1,450	1,900	2,350	2,740
Test 26	670	1,200	1,615	2,060	2,450
Av	698	1,266	1,651	2,094	2,531
Std dev	258	130	214	269	277

APPENDIX C---PRESSURES FOR SEASONED WOOD CRIB SPECIMENS AT FIVE DESIGNATED DISPLACEMENTS

Load rate, in/min	Designated displacement--				
	0.1 in	0.2 in	0.4 in	0.8 in	1.2 in
0.01:					
Test 1	610	1,063	1,287	1,664	1,844
Test 2	800	1,254	1,489	1,803	2,125
Test 3	540	1,215	1,575	1,929	2,278
Av	667	1,177	1,450	1,799	2,082
Std dev	115	100	147	132	220
0.05:					
Test 4	47	660	1,470	1,840	2,185
Test 5	750	1,119	1,380	1,765	2,170
Test 6	532	1,210	1,570	2,100	2,840
Av	443	996	1,473	1,901	2,398
Std dev	359	294	95	175	382
0.10:					
Test 7	430	1,150	1,495	1,805	2,100
Test 8	175	910	1,420	1,880	2,335
Test 9	590	1,344	1,745	2,015	2,394
Av	398	1,134	1,553	1,900	2,276
Std dev	209	217	170	106	155
0.50:					
Test 10	230	1,250	1,940	2,350	2,740
Test 11	225	1,060	1,600	1,970	2,320
Test 12	165	1,400	1,790	2,340	2,890
Av	440	1,237	1,796	2,220	2,650
Std dev	36	170	140	216	295
1.00:					
Test 13	300	850	1,400	1,890	2,380
Test 14	680	1,260	1,670	2,060	2,400
Test 15	320	830	1,530	2,175	2,740
Av	310	840	1,465	2,032	2,560
Std dev	213	242	135	143	202

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