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Rating the Strength of Coal Mine Roof Rocks

UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

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Cover: Greg Molinda, U.S. Bureau of Mines geologist, collects field data to determine the cause of roof failure in a Virginia Coal Mine. (Photo: David K. Ingram, Pittsburgh Research Center, U.S. Bureau of Mines).

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Rating the Strength of Coal Mine Roof Rocks

By Gregory M. Molinda and Christopher Mark

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Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea Lydia Graham, Director

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The characterization of coal mine roof rock is extremely important for the purposes of hazard assessment, reinforcement, and entry design. The Coal Mine Roof Rating (CMRR) has recently provided a breakthrough in roof characterization and has found acceptance in the coal mining industry. Through a procedure of simple field testing and guided observation, a ranking of relative roof strength is easily calculated for numerical modeling, comparative bolt optimization, or statistical analysis of roof failure in variable geology.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	psi	pound (force) per square inch
in	inch	%	percent

Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

RATING THE STRENGTH OF COAL MINE ROOF ROCKS

By Gregory M. Molinda[1] and Christopher Mark[2]

ABSTRACT

The characterization of coal mine roof rock is extremely important for the purposes of hazard assessment, reinforcement, and entry design. The U.S. Bureau of Mines (USBM) Coal Mine Roof Rating has recently provided a breakthrough in roof characterization and has found acceptance in the coal mining industry. Through a procedure of simple field testing and guided observation, a ranking of relative roof strength is easily calculated for numerical modeling, comparative bolt optimization, or statistical analysis of roof failure in variable geology.

The Ferm pictorial classification of coal measure rocks is also widely utilized in coalfield exploration. Although extremely useful as an alternative to conventional geologic description, no material properties are provided that would be suitable for engineering solutions. To remedy this problem, the USBM has tested over 30 common coal measure roof rock types for axial and bedding strength. More than 1,300 individual point load tests have been conducted on core from 8 different coal mines representing the full range of common coal measure rocks. These data, along with data from roof exposures in 19 coal mines, were used to generate strength ratings for common lithologies found in the pictorial guide. The USBM core and roof exposure properties database has been merged with the picture classification to provide, for the first time, a simple, clear guide from field identification of core to the associated mechanical strength of the rock. For 33 of the most common roof rocks, the axial and diametral point load strength, as well as the ultimate unit rating, is overprinted onto the photograph. The information can be used as a quick field roof appraisal and as a workstation reference for more comprehensive analysis.

The unit ratings for each rock type indicates that the weakest rocks are fireclays, claystones, and shales with coal streaks. Mixed rocks with silt and sandstone layers are of moderate strength, and sandy shales, true sandstones, pebble conglomerates and limestones are the strongest roof rocks. Point load data illustrate the directional weaknesses of shales and "mixed" rocks such as "stackrock," and can be used to indicate their susceptibility to horizontal stresses. The high strength and low anisotropy of sandstones and carbonates can be an indicator of the magnitude of horizontal stress fields. If these strong rocks can be crushed or "cut," the magnitude of the horizontal stress field is high.

The variability of properties within the categories found in the pictorial guide is demonstrated and a field example of uphole roof property variability is presented.

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INTRODUCTION

It is both intuitive and proven through long experience that stronger rocks make better roof. Recent studies have shown that even gate roads with Analysis of Longwall Pillar Stability factors of less than 1.0 can be successful if they have strong roof rocks (*1*).[1] Of course, other factors, including roof support, play a role in roadway stability, but strong roof rocks have the most influence. The variability of the composition and thus the strength properties of roof rocks has historically derailed attempts to treat rock as a building material and apply engineering principles to design. This problem applies to both the rock matrix itself and to the geologic structures that disrupt the continuity of bedded rocks. The USBM and many others have described the special structures and rock associations that weaken coal mine roof (e.g., faults, rolls, clay veins, pinchouts, and paleochannels). These geologic structures present local situations that are addressed on a case-by-case basis. Their remediation has also been extensively described (*2-10, 35*). That leaves the consideration of "normal" roof rocks formed in the myriad of depositional environments common to coal basins (*11-12*). Although there is an almost infinite variety of roof rocks, generally they can be broken down into several dozen rock types that comprise the majority of common roof sequences. These roof rocks have been the subject of USBM strength testing and have been rated based on their inherent strength.

PICTORIAL ROCK CLASSIFICATION SYSTEM

A color pictorial classification system of common coal measure roof rocks was previously developed to provide geologists, engineers, and drillers with a standard by which to group rocks. "A Guide to Cored Rocks in the Pittsburgh Basin" by J. C. Ferm and G. C. Smith is a field guide featuring color photographs of named rock types with an attached reference number (*13*). This guide has found wide acceptance throughout the coalfields and fills a longstanding need to standardize geologic description into a numerical system. The name and number of the rock depends on criteria including angle of bedding, color, grittiness, nature of fracture, size of inclusions, carbonate content, and hardness. A series of questions guides the user in a flowchart manner to the correct picture. This guide has been widely accepted by technical personnel because of its use of pictures and because the number system lends itself well to computer cataloging and analysis. The primary application has been as an aid in exploration core logging.

Correctly naming a rock type is the first step toward comprehensive roof rock characterization. For a number of reasons it becomes necessary to know specific mechanical properties of a rock type for the purpose of determining its performance as a roof material. All of the properties that are included in the Ferm classification, and others, can be combined to determine whether or not the immediate roof sequence will be weak or strong. In this study, the USBM conducted extensive laboratory testing of rock strength properties, as well as compiled rock properties from underground exposures. The purpose of this testing and evaluation program was to merge pictorial identification of roof rocks with engineering properties for design. The product of this effort is presented in this report.

COAL MINE ROOF RATING (CMRR)

The desire to classify these rock types into "strong" and "weak" categories is a natural tendency that facilitates the documentation of roof performance and ultimately the design of openings and reinforcement. Numerous rock mass and roof classifications have been devised (*14-18*). These classifications are based on mechanism of failure, shape of fall, lithologic association, mechanical properties of rocks, stress regimes, and other criteria. From this body of work and USBM research, a roof classification was developed that is practical and appropriate to coal measure roof strength evaluation (*19*).

The Coal Mine Roof Rating (CMRR) is designed to evaluate the properties that weaken rocks, and rank the competence of bolted roof on a 0-100 scale. It uses the most important properties of coalbed discontinuities, such as bedding cohesion and spacing, strong beds, and intact rock strength to indicate structural stability. These properties are derived from underground exposure and rock core. Within the CMRR, the unit rating is the strength value given to each lithology within the bolted interval. Even though the composition of coal measure roof rocks may vary tremendously, the unit rating of the rock can accurately portray its strength, and can be used to design support and predict stability. This unit rating summarizes the physical properties of each rock type and represents its strength. Through mechanical testing and core analysis, as well as calculation from underground exposure, the unit rating has been assigned to selected rock types in Ferm and Smith's "A Guide to Cored Rocks in the Pittsburgh Basin" for easy reference.

By merging two geotechnical tools, pictorial rock classification, and mechanical properties testing (CMRR), a new tool can now be used by design engineers. Roof rocks can now be systematically classified by picture, and their strength properties can be directly applied to pillar design and roof bolt selection.

[1]Italic numbers in parentheses refer to items in the list of references preceding the appendix.

ROOF ROCK STRENGTH PROPERTIES

The U.S. Bureau of Mines has compiled a database of rock properties including the unit rating of over 30 common coal measure roof rocks. These rock properties were obtained from underground exposures and rock cores of the roof from both surface and underground. The purpose of gathering these data is—

1. To determine the relative structural competence of different roof rocks.
2. To match strength properties with pictorial guide equivalent rock for easy reference of rock properties for CMRR calculation.
3. To demonstrate the variability of strength properties within rock types.
4. To document anisotropic properties of rock types for use in explaining failure modes and selection of reinforcement.

The strength properties shed some light on the susceptibility of individual rock types to both horizontal and vertical stresses. Rock types with associated properties are classified by the popular Ferm method to give operators a reference for calculating CMRR values when actual testing is impossible. Additionally, reference strength values attached to pictures of actual roof rocks should give numerical modelers more accurate physical properties to use to represent roof strata.

POINT LOAD TESTING

It is well known that most coal measure rocks are weaker in tension than compression. This is because their bedded nature, and the predominance of clay minerals in roof sequences, provides weak interfaces and little effective cementation. This is not true of coarse clastic rocks such as sandstone and conglomerates. Their lack of directional weakness is what makes these rocks strong roof rocks. The other structural property of coal measure rocks is the axial strength (perpendicular to bedding). This is determined by the nature of grain to grain contacts, cementation, and the material strength of silica relative to clay minerals. Rocks that are strong perpendicular to bedding can form good anchorage for roof bolts or function as strong beam formers in the bolted interval. It was decided that a good way to characterize the common coal measure roof rocks was by measuring the bedding strength (cohesion) and the axial strength (perpendicular to bedding). In underground exposures of the roof, field tests are used on hand-sized samples of rock to test cohesion and compressive strength (*19*). These index tests (hammer and chisel) do not work well with core. Therefore, the point load test is used for measuring these properties.

Point load testing has long been used as a strength index (*20*). It has been successfully correlated with unconfined uniaxial strength of rocks (*20-23*). Figure 1 represents data from USBM testing and shows a correlation between Point Load compressive strength and unconfined compressive strength measured in a load frame. There is good agreement between the two methods of testing.

The diametral strength alone has been used to indicate roof quality (*24-25*). Its use in scale modeling has also been suggested (*26*), although most often point load indices have been used in conjunction with classification schemes (*20, 27-30*). When applied perpendicularly to bedding, the resulting point load value is related to the Unconfined compressive strength. When applied parallel to bedding the measured value is related to the tensile strength or, generically, the "cohesion" along the bedding.

There are some significant advantages to point load testing.

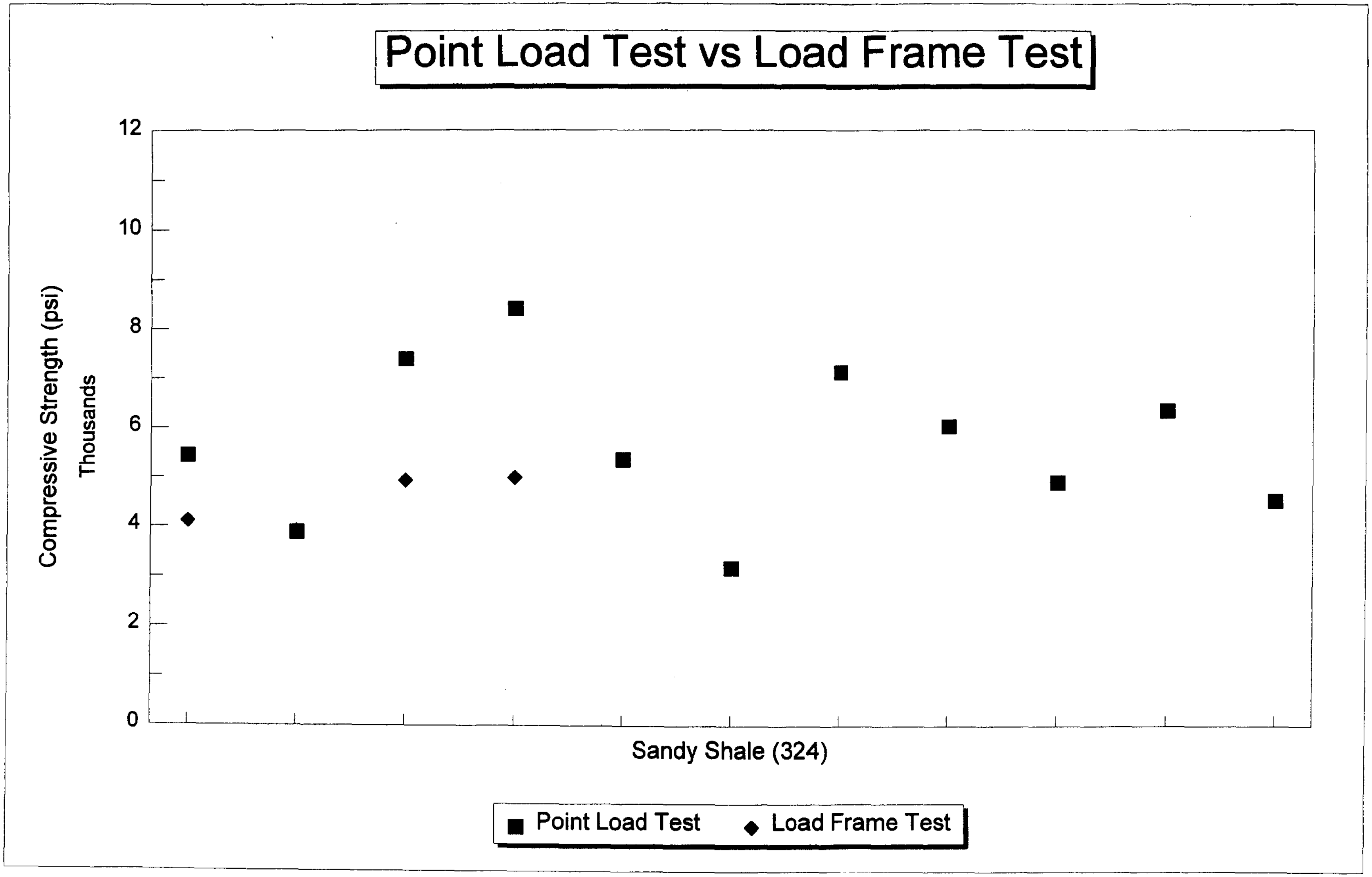
1. It is well correlated with conventional load frame testing results.
2. Numerous tests can be performed because the sample preparation is minimal, small samples can be used, and the test itself is quick and simple.
3. The test apparatus is inexpensive and portable.
4. Results show less scatter because the small sample size eliminates the defects found in larger cores.

More than 1,300 point load tests were conducted on core from eight different mines in Pennsylvania, Illinois, Ohio, Kentucky, and Wyoming. The core was provided by active mines and was all 2- and 3-in core. Most of the core represented rock units that formed the immediate roof (10 ft). The rest of the core that was tested represented innerburden and overburden, of interest because of longwall mining.

Thirty rock types, as identified by Ferm numbers, were point load tested. These lithologies represent the majority of the common roof rocks that occur in coal measure rocks. They range from fireclays to limestones. Although Ferm and Smith's "A Guide to Cored Rocks in the Pittsburgh Basin" lists more than 100 rock types, many of these lithologies are rare or are small variations of more common rocks.

Samples were prepared and sized according to International Society of Rock Mechanics (ISRM) recommendations (*21*). Testing procedures included hand pump loading of samples with peak failure loads recorded by datalogger. Guidelines on the proper failure type were followed, and results from tests that did not fail completely were discarded. Because cores were mostly obtained at

Figure 1



Correlation of axial compressive strengths from point load testing and load frame testing.

times up to 2 to 3 years after drilling, the moisture content of all cores was similar and was considered to have affected the rock strength uniformly.

The number of samples tested varied between 1 for several rock types and over 80 depending on the amount of core available.

A portable point load apparatus, equipped with a pressure transducer and a datalogger, was used for testing (figure 2). The data were transferred to a Lotus spreadsheet, and axial and diametral strength values were calculated according to the following relation:

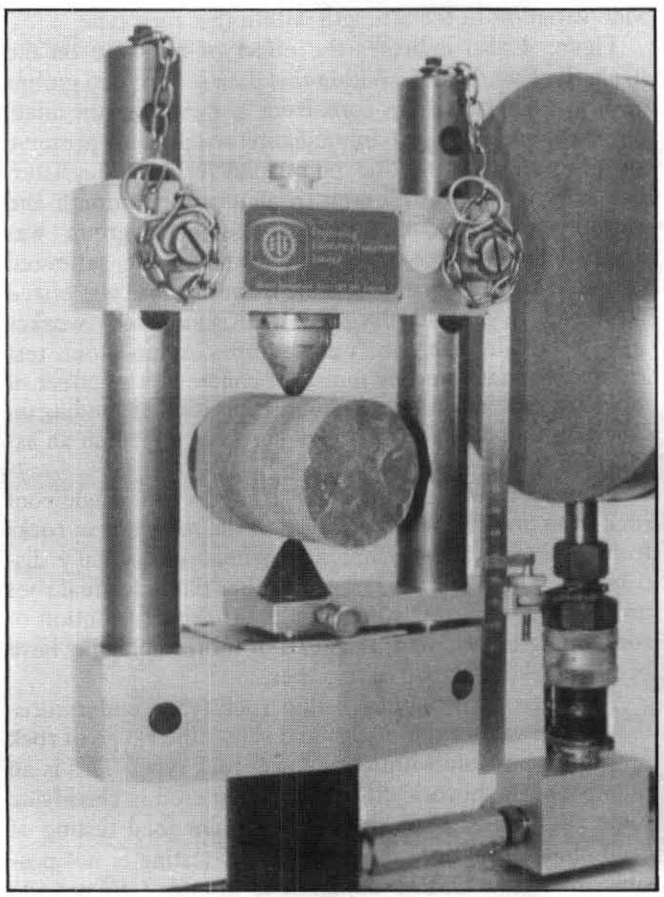
$$I_s = \frac{P}{De^2}$$

where I_s = index of strength,

P = point failure load,

De = effective diameter

Figure 2



Point load testing apparatus.

$= 4A/\pi$ for Axial, Block, or Lump Tests.

A = Width × Diameter,

with core size correction to 50 mm (ISRM standard):

$$I_s(50) = F \times I_s$$

$$F = (De/50).$$

The $I_s(50)$ value was then converted to unconfined compressive strength by the factors given by Vallejo: 12.5 for rocks of similar strengths to shales and 17.4 for rocks of similar strengths to sandstones (22). Vallejo determined that the correlation between $I_s(50)$ and compressive strength varied with rock type, which was designated as either shale or sandstone. Separate regression equations yielded a conversion factor of 12.5 for shales and 17.4 for sandstones. In the present study, for purposes of correlation, the 30 rock types were divided into two categories: clay-rich rocks, like fireclays, shales, and mixed mudrocks, were assigned the 12.5 conversion; sandstones and carbonates were assigned the 17.4 conversion (table 1). These conversion values were derived by correlation of the two strength tests from coal measure rocks obtained from surface mines in Kentucky, Virginia, West Virginia, and Tennessee.

Strength Perpendicular to Bedding

The axial strength of a rock is an important part of the unit rating and, in part, determines the ability of the rock to function as a roof beam. The USBM measured the average axial point load strength of the regular roof rock types, grouped into common lithologies (table 2; figure 3). Table 2 represents all of the rock strength testing, as well as the calculated unit rating for each rock type. By identifying the rock type by Ferm No., one can determine the description, axial and diametral summary strengths, location by mine name and source (core or fall), and, finally, the unit rating. For example, for Ferm No. 114, a black shale has an average axial strength of 6,367 psi and an average diametral strength of 1,512 psi. A unit rating of 47 was calculated from core obtained at an Illinois mine. Unit ratings of 37, 40, and 30 were calculated from roof falls at two Pennsylvania mines. The average is 39 for this rock type.

The range of axial strengths is from less than 1,300 psi (fireclay) to more than 18,000 psi (limestone). There is a broad band (14 rock types) of "mixed rocks" of midrange strength. This designation refers to rocks composed of several lithologies (i.e., shaley limestones, shale and interbedded sandstone, sandy fireclay with limestone nodules, etc.). Physical properties of these rocks are a combination

Table 1.—Conversion factors applied to different rock types

Ferm No.	Conversion factor
014	12.5
020	12.5
113	12.5
114	12.5
119	12.5
122	12.5
123	12.5
124	12.5
127	12.5
137	12.5
147	12.5
229	12.5
237	12.5
322	12.5
323	12.5
324	12.5
325	12.5
327	12.5
332	12.5
337	12.5
357	12.5
437	12.5
541	17.4
543	17.4
544	17.4
749	17.4
772	12.5
782	12.5
802	12.5
804	12.5
894	17.4
896	12.5
904	17.4
906	17.4
994	17.4

of the properties of the individual lithologies. They occupy the middle ground in the strength scale. It is important to test a number of samples of rocks from the "mixed" group because of the variability of samples and the possibility of bias toward one rock type or another. A sample size analysis shows that the required number of samples depends on the variability of the rock type (table 3). For highly variable rocks, such as a sandy shale, it is necessary to test more samples to be 90% confident of obtaining a representative average within a 2,000 psi spread. To narrow the confidence interval to 1,000 psi, more samples are necessary. For the purposes of generating a unit rating, it is probably sufficient to stay within the 2,000-psi confidence interval. Strength properties of the "mixed" rock types exhibit wide variation based on composition. As an example, the roof at an eastern Kentucky mine is composed of a "stackrock." This rock consists of an alternating sequence of sandstones and shale. The rock is much weaker when the percentage of shale bands increases.

There is wide variability in the composition, structure, and strength of coal measure rocks. Because of the nature of sedimentary deposition, rapidly changing hydraulic environments introduce sand, silt, and clay in varying amounts. It is primarily these components that determine the strength properties of each rock. Generally, the more coarse clastics in the rock matrix, the stronger it is axially, although other components (cement) and discontinuities also affect its strength. As the proportion of fine silt and clay deposition increases, the rock bedding is more closely spaced and prominent. This tends to weaken the rock fabric, and this effect is seen in the "mixed rock" group. Additionally, as clay content increases in a sandstone matrix, the clay "cement" does not reinforce grain contacts and leads to matrix weakness. Also, highly porous rocks are not particularly strong because of low and weak cement content.

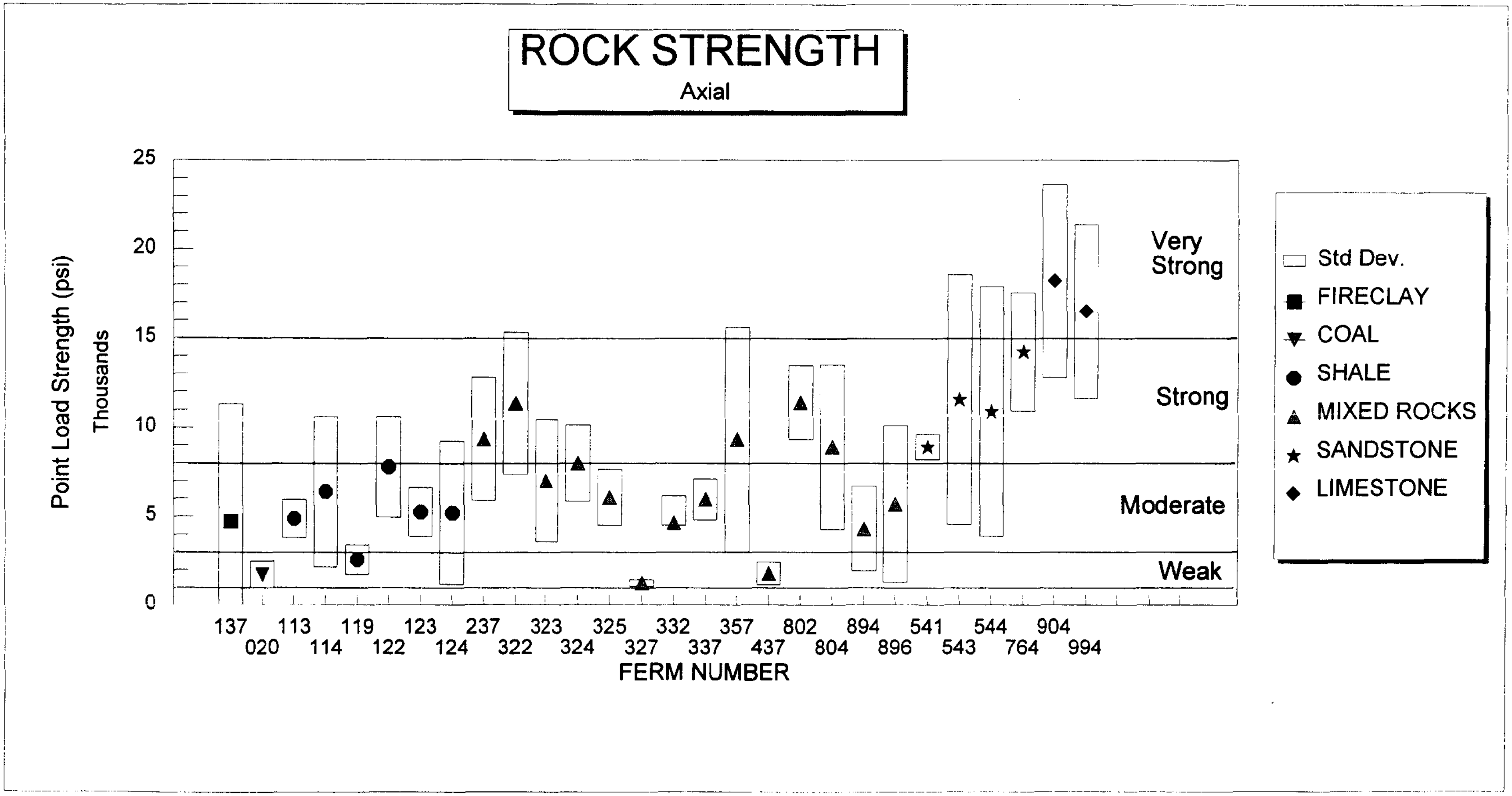
The Ferm classification uses several criteria (color, grittiness, bedding, fracture, carbonate content, etc.). Variability within these properties can be great even within single rock groups. Figure 4 shows the axial strength of samples of Ferm No. 544, a gray massive sandstone. There are six distinct populations within this rock type, distinguished by the average axial point load strength shown above the populations. Samples of sandstone from cores of three mines are represented. Even though these samples are best identified by Ferm No. 544, there is still wide variation in the strength within this rock type.

Figure 4 also indicates the effect of moisture on the strength of sandstone. Within this data set are two groups of Sewickley sandstone core from a Pennsylvania mine. The "wet" samples were immediately wrapped to preserve moisture after coring and point load tested 1 day later. The "dry" group was allowed to air dry for 1 month and was then point load tested. The "dry" group was significantly stronger after 1 month than the saturated samples. Another group of shale from the core was tested "wet" and "dry." The dry shale was significantly weaker after 1 month than the "wet" group. A limestone test group was unaffected by moisture content. The effect of moisture content is evident, though opposite, depending on lithology, and for this reason, all core was tested on an as-received "dry" basis.

Figure 5 represents the axial strengths of a single roof rock from one Pennsylvania mine. Axial strengths of rocks from a single lithology are approximately normally distributed. This is a good test of whether the individual roof unit has been correctly delineated. If the distribution of rock strength is skewed, then two or more units may have been mistakenly grouped together.

This type of variability within rock types underscores the natural variation in rocks, and shows the range of rock properties possible within one Ferm rock type. This is an example of the historic difficulty encountered in classifying some rock types. For this reason, point load testing of each mines' roof core is preferred. If testing is not possible, then the USBM database is intended to provide comparable data for calculation.

Figure 3



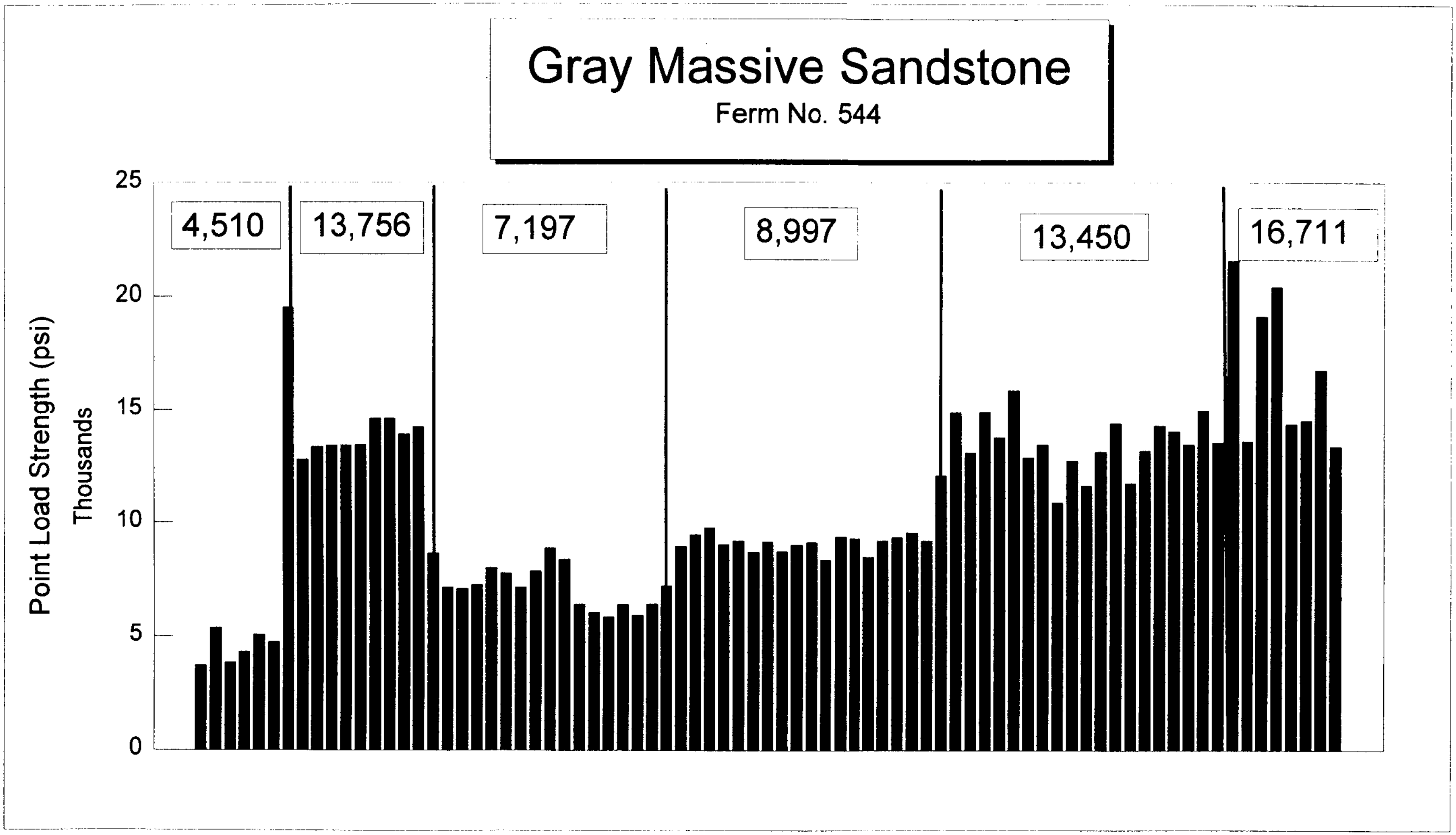
Average point load strength of common coal mine roof rocks measured parallel to the axis of the core.

Table 2.—Common coal measure roof rocks and their point load strength properties and unit ratings.

		Axial strength			Diametral strength			Unit ratings					
Ferm No.	Description	Avg. (psi)	Std. Dev.	n=	Avg. (psi)	Std. Dev.	n=	Mine	State	Core	Under-ground	Avg.	Std. Dev.
014	Slumped Sandy Shale							1	PA	35		35	
020	Coal	1727	747	52	861	345	48	2	WY	30	40	35	6
								1	PA	35,30,31 26	41,37,41		
								3	KY	35,41,43, 35,35,43,35			
								4	WV		25,30,31		
113	Black Shale with Coal Streaks	4870	1063	5	790	223	4	5	OH		31	35	9
								1	PA	32,30,48			
114	Black Shale	6367	4220	16	1512	887	14	6	IL		47	39	7
								7	PA	37,40			
								1	PA	30			
119	Black Shale with Fossil Shells	2557	825	9	1247	561	7	3	KY	40,35,44, 44,31	40	39	5
122	Dark Gray Layered Shale	7770	2805	15	3628	4505	7	4	WV		44	45	1
								8	PA		46		
123	Dark Gray Shale with Coal Streaks	5238	1367	5	1299	573	4	8	PA		35	33	6
								9	PA		27,31		
								4	WV		37		
								5	OH		34,29		
								1	PA	32,39,40,30, 40,31,29,30 25,28,31,24, 39,32,29,44	34,44,35,36 29		
124	Dark Gray Shale	5196	4006	64	1148	552	43	10	PA		41,30	36	7
								2	WY	34,30	27		
								11	PA	38			
								1	PA	40,35,41,33	29		
								3	KY	30	43,48		
								7	PA	47,37			
127	Dark Gray Fireclay				1284	877	7	10	PA		14	30	4
								12	OH		32		
								11	PA	35,39			
								1	PA	22,20,38			
								13	WV		30		
137	Light Gray Green Fireclay	4719	6580	2	920		1	3	KY	28,36,24	24	28	6
147	Green Claystone							14	OH		29,21	30	9
								11	PA		39		
237	Light Gray Green Fireclay with Limestone Nodules	9329	3435	4	2319		1	1	PA				
322	Dark Gray Shale and Interbedded Sandstone	11335	3966	28	2508	1357	30	15	WV		47	48	9
								16	WV		40		
								7	PA	37,59,58			
								1	PA	48			
323	Dark Gray Shale with Sandstone Streaks	6990	3432	27	1548	726	18	1	PA	37,40		40	5
								3	KY	44,35			
								7	PA	47,35			
324	Dark Gray Massive Sandy Shale	7980	2150	86	1344	681	47	17	WV		44,49,49	47	7
								1	PA	48,55,35,43 39, 38			
								18	IL		48,43		
								19	PA	40			
								3	KY	50			
								9	PA		59,60		

325	Dark Gray Massive Churned Sandy Shale	6063	1564	16	1914	1622	27	17 11	WV PA	 53,42,49	40 57	48	7
327	Dark Gray Sandy Fireclay	1253	184	8				3	KY	29		29	
332	Light Gray Green Shale and interbedded Sandstone	4653	1482	36	1482	904	34	6 2 3	IL WY KY	 56,43 40	40	44	8
337	Light Gray Green Sandy Fireclay	5953	1155	8	5660	4374	8	1	PA				
357	Red and Green Sandy Claystone	9297	6289	9				1	PA				
437	Light Gray Green Sandy Fireclay with Limestone Nodules	1786	634	17	707	248	11	1	PA				
541	Gray Crossbedded Sandstone	8886	701	5	3552	1824	5	1 3 2	PA KY WY	58,59 72,59 67		63	6
543	Gray Sandstone with Shale Streaks, rippled	11550	7003	68	4129	2063	50	14 1 2 11 3 7 20 21 17	OH PA WY FA KY PA OH KY WV	 74,95,90,54 51 92,53 92 74	32 63 77 56,61,53,57, 58,51,44 49	63	18
544	Gray Massive Sandstone	10876	3914	80	13632	5509	23	22 21 1	WV KY PA	 92 74	92 50	77	20
749	Gray Sandstone with Coal Spars							13 5	WV OH		43,54 32	43	11
764	Hard Quartz Pebble Conglomerate	14227	3319	10	9762	5116	9	1	PA	46		46	
772	Shale Breccia	3231	267	3									
782	Shale Pebble Shaley Limestone Breccia							3	KY	74,85,74		78	6
802	Layered Fine-Grained Shaley Limestone	11366	2083	4	2130	641	4	6	OH		63	63	
804	Massive Fine-Grained Shaley Limestone	8884	4614	4	5889	4379	4						
894	Massive Fine-Grained Shaley Limestone	4305	2374	7	2018	476	2	3	KY	35		35	
896	Fine-Grained Shale Limestone with Limestone Nodules and Fossil Shells	5684	4376	22	1300	325	11						
904	Massive Fine-Grained Limestone	18203	5442	25	18397	3290	16	6	OH		100	100	
906	Nodular Fine-Grained Limestone							5	OH		83,100,100	94	9
994	Massive Fine-Grained Limestone with Fossil Shells	16496	4891	3	11997		1						

Figure 4



Distribution of axial point load strength for gray massive sandstone, Ferm No. 544.

Table 3.—Sample size analysis for selected rock types

Mine	Rock type	Axial strength (average)	Standard deviation	90% confidence 2,000 psi sample size (N)	90% confidence 1,000 psi sample size (N)
7 . . .	124	11,054	2,706	5.0	19.8
	322	12,279	1,873	2.4	9.5
21 . .	543	18,257	3,134	6.6	26.6
	544	16,711	3,258	7.2	28.7
1 . . .	324	5,817	1,649	1.8	7.4
	543	7,119	982	0.7	2.6
11 . .	543	16,735	4,260	12.3	49.1
2 . . .	543	3,423	640	0.3	1.1

Forty percent of the rock types tested fall in the strong to very strong categories for average axial strength. This includes all of the limestones, and true sandstones, as well as five different "mixed" rocks (figure 3). These mixed rocks are, respectively, fireclay with limestone nodules, shale and interbedded sandstone, sandy claystone, fine-grained shaley limestone, and massive fine-grained shaley limestone. Three of these "mixed" rock types have limestone components, and one sandstone, which may account for the rocks' strength. Most of the rest of the "mixed" rock and shales fall into the moderate category. Rocks in the "weak" to "very weak" categories include fireclays, which have inherently weak fabrics or internal defects due to loading of originally pliable sediments.

Strength Parallel to Bedding

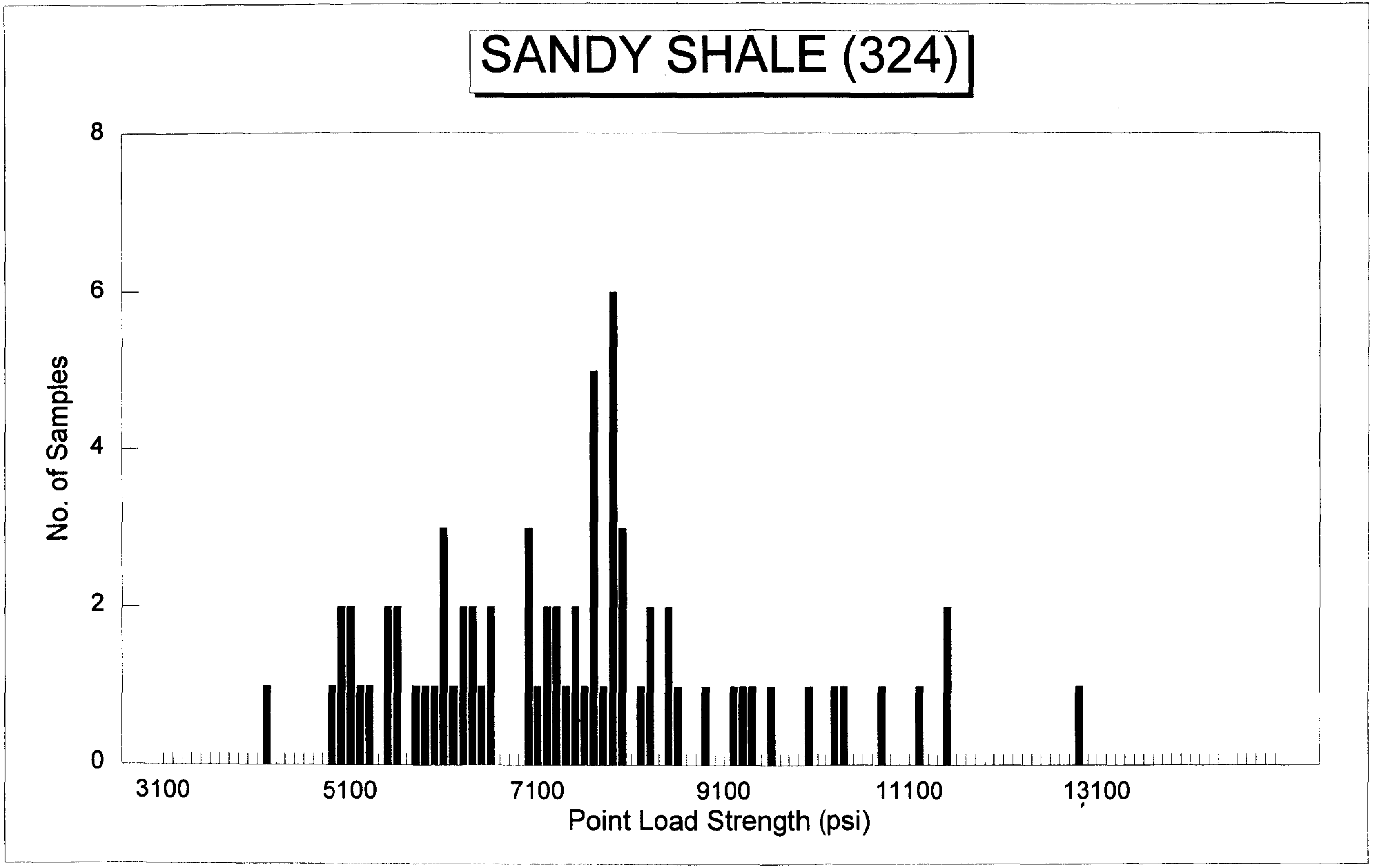
The axial strength of rock fabric is only one factor that can affect the unit rating and the integrity of the roof sequence. The strength and frequency of bedding and other discontinuities are also very important to the unit rating and ultimately the CMRR for the entire bolted roof. Experience has shown that highly laminated rock is more susceptible to horizontal stress (*31*). As the nature and effects of horizontal stress become better known, it is becoming apparent that this stress on the roof is much greater than previously thought, and is responsible for numerous roof failures (*32-33*). Additionally, loss of bolt tension in rocks with weak bedding can begin "unraveling" of the roof, which could lead to a fall. Other discontinuities, aside from bedding, present similar weaknesses. When randomly oriented slickensides from slump deposits or compacted muds occur with a high frequency, diametral strength is very weak. Often these rocks fall immediately after exposure by mining; presenting a hazard, and decreasing the coal quality.

The diametral strength parallel to bedding was measured by point load testing for the range of common coal measure roof rocks. Figure 6 is the average diametral strength for this suite of roof rocks. The range of diametral strengths is broken into "weak," "moderate," and "strong." Approximately one-half of the rock types have diametral strengths in the "weak" range (less than 2,000 psi or hand-break strength). This does not necessarily indicate a rock that will be a weak roof member. The frequency and persistence of the weak zones also are considered in the calculation of the unit rating, which is the value indicating total strength. Most of the fireclays, shales, and "mixed rocks" fall below the 2,000 psi mark, which represents the "hand-break" range in core. When moving into the sandy shale, sandstone, limestone range, diametral strength increases markedly. This is easily understood because the effects of bedding become less prominent, and clastic contacts and cementation tend to increase. In addition to being less susceptible to tensile failure (sag), these rocks are also less likely to shear on bedding under the effects of horizontal stress. The break between "moderate" and "strong" is 5,000 psi. This represents the midpoint of all point load tests over 2,000 psi. In this "moderate" strength group are gray layered shale (122), a number of mixed rocks (237, 322, 325, 802, 894), crossbedded sandstones (541), and sandstone with shale streaks (543). Rocks that fall into the "strong" category (>5,000 psi) include massive sandstone (544), sandy fireclay (337), quartz pebble conglomerate (764), fine-grained limestone (904, 994), and shaley limestone (804).

Anisotropy

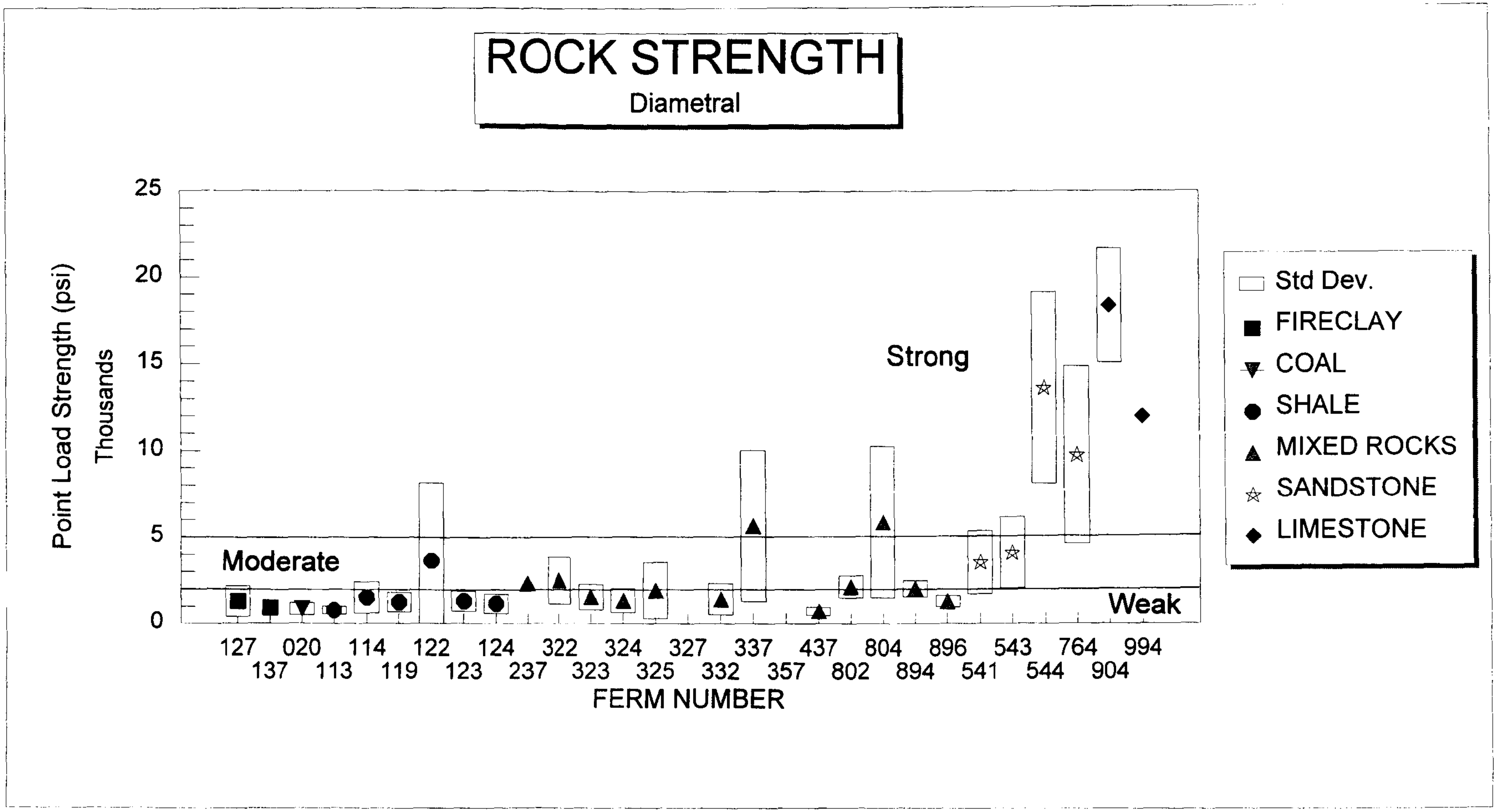
Figure 7 represents the anisotropy of various roof rocks. Again the roof rocks are represented from fireclay to limestone and a trend is apparent. Anisotropy decreases from shales, and highly bedded rocks, through mixed rocks to sandstones and limestones. This indicates that a rock with high anisotropy like No. 322, shale and interbedded sandstone, would be weak when loaded diametrally on the shale streaks, but strong when loaded axially due to the sandstone bedding. The rocks comprising the low end members (sandstone/limestones) have low anisotropy because they are more massive and exhibit less bedding discontinuity. These rocks are equally strong in each direction. The effect on limestone is to resist failure equally well in all directions. The anisotropy of roof units can indicate the shape of a roof fall. Whereas strongly bedded and highly anisotropic rocks tend to "stairstep" and create flat-topped falls, massive isotropic rocks like limestones tend to form blocky, inverted V-shaped falls. The degree of rock anisotropy can have large effects when considering horizontal stress and reinforcement. A highly anisotropic rock, i.e., a laminated shale, would react to

Figure 5



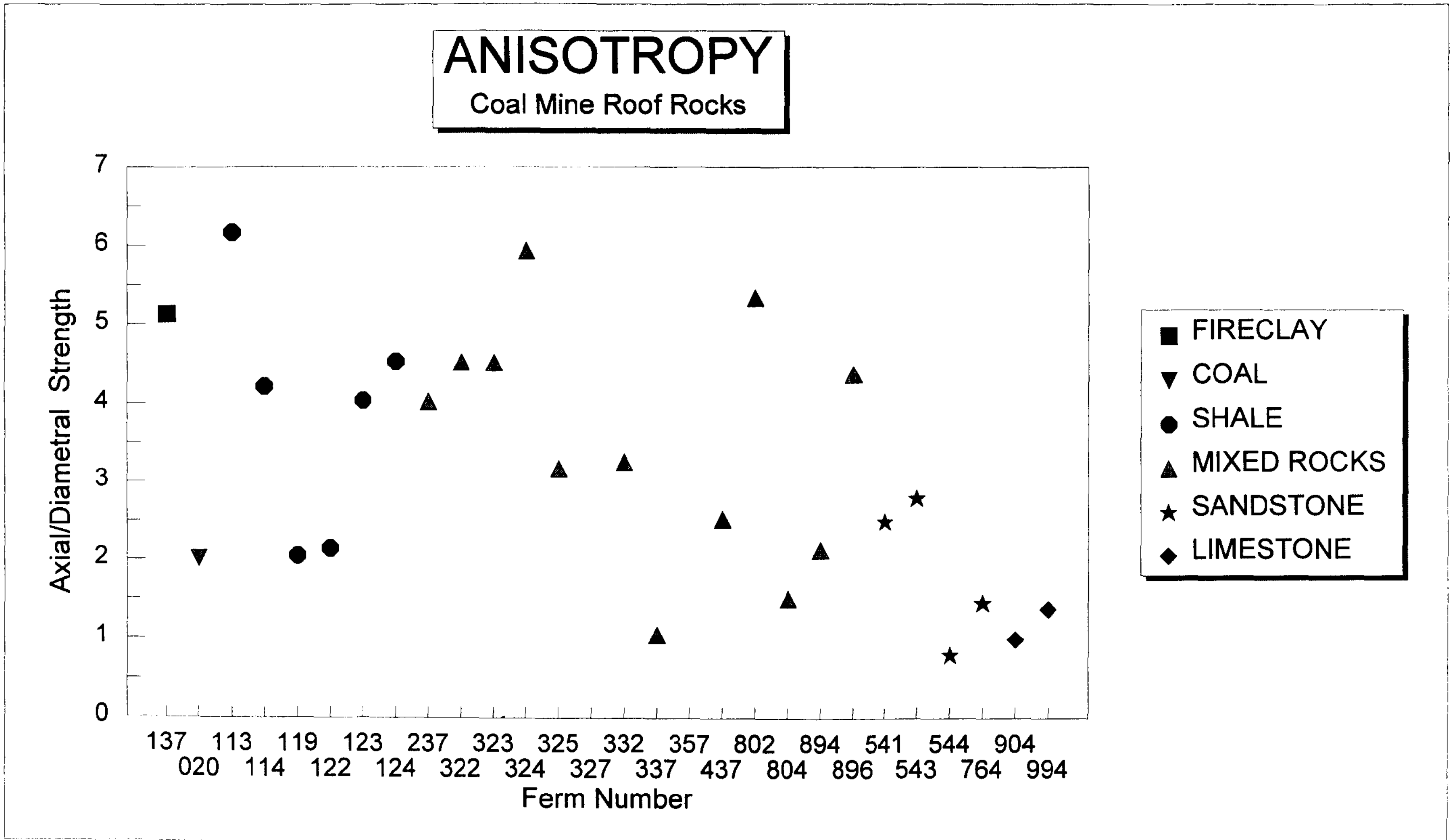
Normal distribution of axial point load strength for the immediate roof at a Pennsylvania mine.

Figure 6



Average point load strength of common coal mine roof rocks measured perpendicular to the axis of the core.

Figure 7



Point load strength anisotropy of common roof rocks.

horizontal stress by delaminating and bulking, possibly resulting in a fall. Highly anisotropic rocks tend also to react to horizontal stress by forming cutters. More massive rocks are resistant to cutters. Bedding plane weakness can also impact roof bolting practice. Fully grouted bolts appear to work better in weak bedded rocks.

MOISTURE SENSITIVITY

Another rock property that affects the unit rating and the ultimate strength of the rock is moisture sensitivity. This property is estimated by a water immersion test and a series of observations about the cracking and sloughage of the sample (*19*).

Depending on the clay content (type and amount), the degradation of a rock from moisture exposure will affect its beam building value and could cause loss of bolt tension due to skin deterioration. Table 4 shows the results of moisture exposure in selected roof rocks over a two month period. The values are calculated as shown in Molinda and Mark (*19*).

Most of the degradation from moisture occurs in the first day after exposure. In fact most occurs during the first 1 to 4 hours. After almost two months of water immersion, further effects were not observed. As expected, the fireclay is the most sensitive with effects diminishing as the clay content found in other rock types decreases. Effects of moisture sensitivity may also be estimated by dry observation of mineral coatings and clay swelling, but the following data can act as a guide to operators in the absence of actual testing.

Table 4.—Moisture sensitivity of common coal mine roof rocks

Ferm No.	Description	4-h submersion	24-h submersion	2-month submersion
124	Gray shale	0	0	0
020	Coal	0	0	0
322	Shale and interbedded sandstone	0	0	0
325	Sandy shale	-2	-2	-2
543	Sandstone with shale streaks	0	0	0
327	Sandy fireclay	-7	-7	-7
323	Shale with sandstone streaks	-5	-5	-5
544	Massive sandstone	0	0	0
114	Black shale	-5	-5	-5
127	Gray fireclay	-25	-25	-25
122	Layered shale	-4	-4	-4
113	Black shale with coal streaks	0	0	0
313	Black shale with sandstone streaks	0	0	0
112	Black layered shale	0	0	0
772	Shale breccia	-6	-9	-9
904	Fine-grained limestone	-2	-2	-2
447	Claystone with Limestone nodules	-6	-6	-6
022	Coal with bone layers	-4	-4	-4

NOTE:

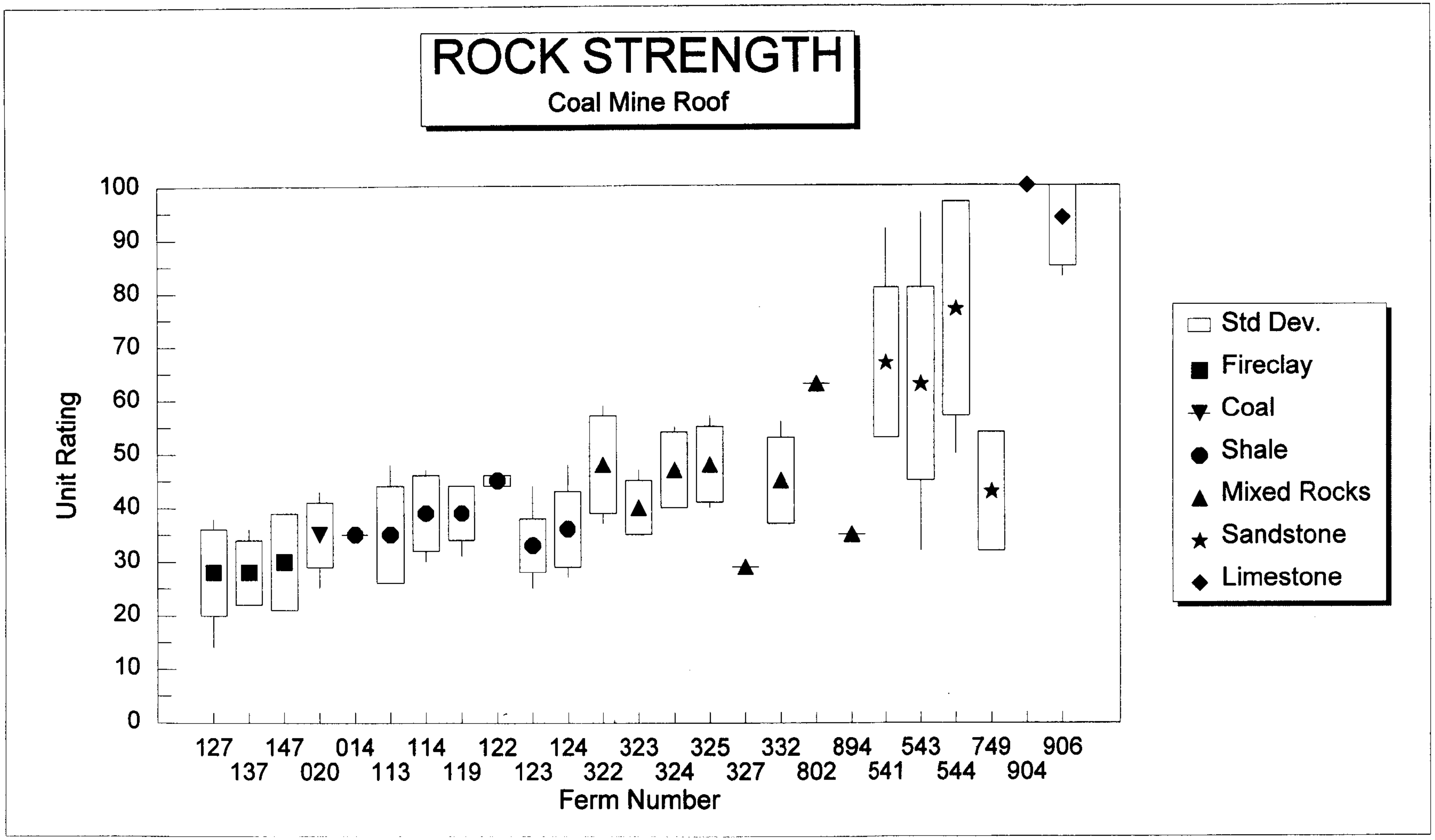
Not sensitive	0
Slightly sensitive	-3
Moderately sensitive	-10
Severely sensitive	-25

UNIT RATINGS SUM UP THE PHYSICAL PROPERTIES

The intent and value of a rating system is that it takes in all of the various physical properties and discontinuity properties and returns a relative value that represents the strength of the strata (*19*). Unit ratings are constructed by summing rock matrix properties and discontinuity properties (*19*). The unit ratings of 27 common coal mine roof rocks were calculated as the average from 173 total unit ratings (table 2). The source of the unit ratings data was both core and underground roof exposures. The result is a picture of the relative strength of the most commonly encountered roof rocks from all U.S. coalfields (figure 8).

All of the unit rating data can be found in table 2. It is broken down by source (roof exposure or core) and mine. Averages have been calculated for each mine and then an overall average unit rating has been calculated and reported for each rock type. The number of data points for each rock type varies due to mine exposure and amount of core tested. The variability within rock types is indicated by the standard deviation of the unit ratings. Often the classification of a rock into Ferm rock types is subjective, increasing the variability in similar rock types. However, it is believed that the Ferm classification is an excellent field system and the attached rock properties can provide a useful reference to the operator. Unit ratings for all of the common roof rocks have been determined, regardless of geologic location and origin. From this

Figure 8



Average unit ratings for common coal mine roof rocks.

information an operator can make a quick assessment of future roof strength and also the final CMRR.

The working range of unit ratings is between 25 (extremely weak claystone and fireclay) and 100 (very stiff limestone). The trend of increasing unit rating from fireclay to limestone parallels the same trend with that of axial strength because this property is an integral part of the unit rating. Generally, however, an increase in coarse clastic content or carbonate signals a decrease in bedding density and the weakness that is associated with it.

By matching the rock type in the roof with the appropriate photograph in Ferm and Smith's "A Guide to Cored Rocks in the Pittsburgh Basin," the strength properties and unit rating, if available, for that rock type can be applied to the CMRR. If the roof rock lies between Ferm rock type categories, the properties and the unit rating can be interpolated. Because moisture sensitivity can weaken the strength of clay-rich rocks, it is helpful to degrade the unit rating when this condition exists. For slightly sensitive rocks, a deduction of 3 points is made; for moderately sensitive rocks, a deduction of 10 points is appropriate. This deduction applies in the assumption that the roof is wet. The pictorial field guide with the attached rock properties is presented in the appendix.

APPLICATIONS IN MINING EXPLORATION AND OPERATIONS

A primary application of the strength data that have been assigned to common coal mine roof rocks is roof hazard assessment during the reserve exploration phase. It is common to gather historical drill data for a property. Many times a rock core was not drilled or the core was not tested. The core database can be used to fill these gaps. If the reserve is new and roof stability experience is limited with certain rock types, the unit rating is provided for use in determining the CMRR. In this way, an operator can begin to assess hazard potential or plan roof bolting schemes. For many rock types the large number of samples tested will provide a better summary analysis of rock strength than would only a few expensive compressive strength tests on a load frame. Additionally, the bedding strength of a rock is an important part of the overall roof strength and is not typically tested with core. This is provided for each rock type. The field guide with rock properties should provide the geologist or engineer with a quick assessment of roof rock strength for preliminary analysis with no testing.

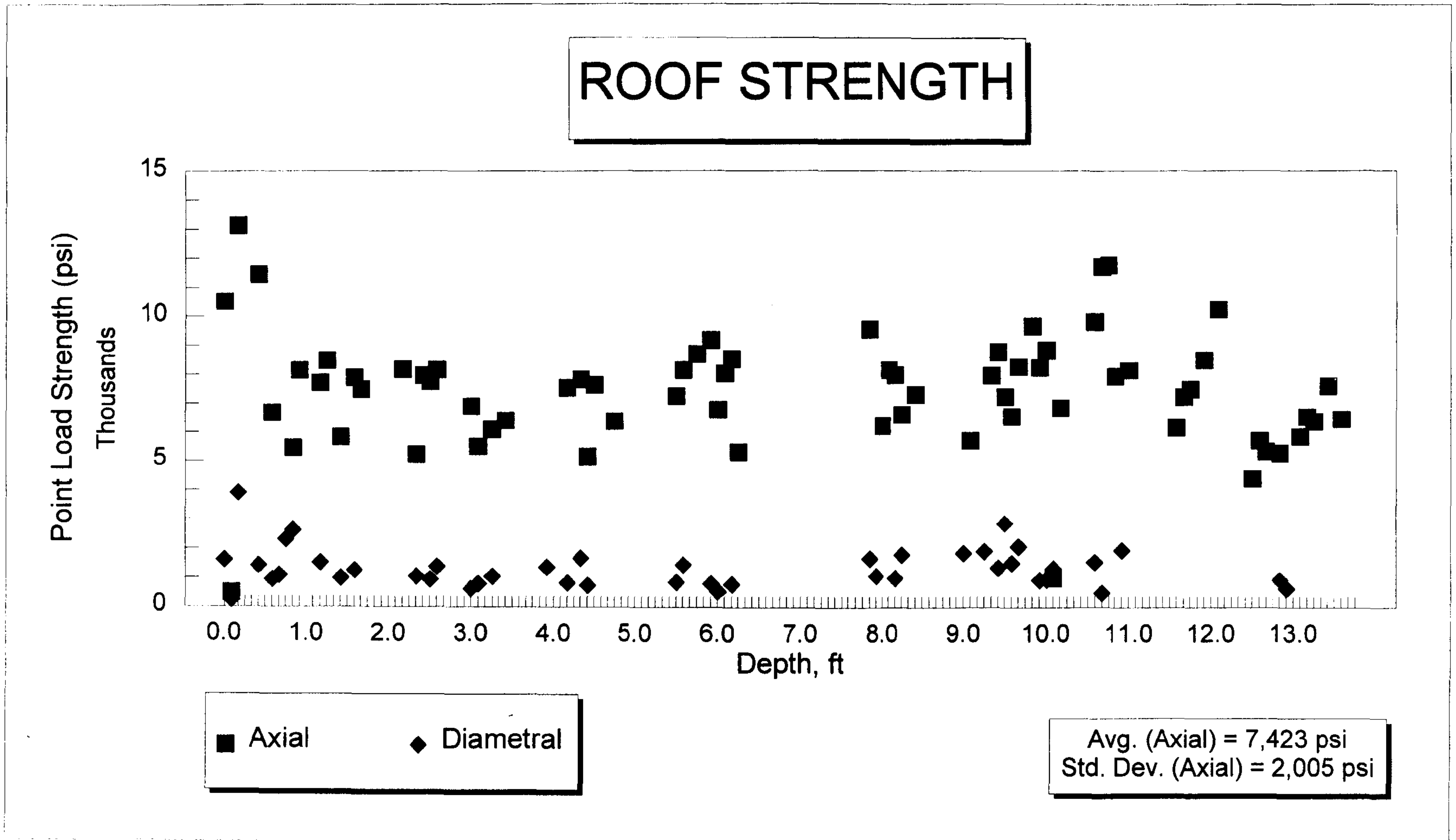
During the operational phase of the mine, the field guide will aid in the historical tracking of roof performance. With each roof exposure (fall, overcast, roof core), a unit rating and CMRR can be calculated to build a database of changing roof lithology, CMRR, and roof bolt performance. Entry stability is a function of numerous parameters, including entry width and orientation, pillar size, reinforcement, horizontal stress, floor quality, etc. Any systematic study of the causes of instability must track the changing roof quality to highlight which variable is responsible for instability.

Numerical models are currently being used to predict ground responses in different loading situations (multiple-seam, pillar recovery, pillar sizing). It is desirable to correctly model the strength properties of the bolted interval and above for best results. The rock properties database can provide this input.

CONTINUOUS COAL MINE ROOF STRENGTH TRACKING

There are several advantages to determining the strength of rock in the bolted interval. This can be done through close (every 6 in) point load testing of core from the bolted interval, or continuous readings from an in hole device like a penetrometer (*34*). One of the reasons for strength testing is roof damage due to horizontal stress. Increasingly, horizontal stress is recognized to be both higher than previously thought, and more often the cause of roof failure (*31, 33*). Stress mapping techniques and actual measurements show that horizontal stress, both in situ and mining-induced, often acts to damage roadways by directional guttering, shearing, and floor heave. It has been observed that different roof strata reacts differently to horizontal stress based on its stiffness (*31*). Strong members within the bolted horizon may act as stress concentrators and fail or buckle to load weaker strata below, causing roof falls. By continuous tracking of changes in roof strength it is possible to identify these suspect strata. Conversely, the CMRR recognizes the beam building advantage of strong beds of sufficient thickness in the bolted horizon. A continuous record of axial compressive strength within the bolted interval via core will help identify a strong bed, which will aid in the calculation of the CMRR. This type of strength tracking allows a complete roof characterization in the bolted horizon and, if possible, should be done at every roof test or instrumentation site. Figure 9 is an example of data obtained from point load testing of 2-in core from the roof of a USBM instrumentation study. It shows relative uniformity of the sandy shale bolted roof up to 14 ft.

Figure 9



Point load strength of sandy shale forming the roof at a Pennsylvania mine.

CONCLUSIONS

A database of two directional strength of common coal mine roof rock has been developed by the USBM. The popular picture classification of strata in Ferm and Smith's "A Guide to Cored Rocks in the Pittsburgh Basin" was used as a base for assigning rock strength data to common roof rocks. This USBM field book is intended to be a reference for operators when rock strength properties are needed in coal pillar design, mine roof assessment, support selection, or numerical modeling. Axial strength and diametral strengths are divided by rock types and show fireclays and shales to be weak, mixed rocks, and sandy shales of moderate strength, and sandstones and limestones to be strong. Strength parallel to bedding is weakest in closely bedded, clay-rich rocks and decreases in sand-rich rocks with poorly developed bedding. This is important in determining the likelihood of rocks to delaminate and fail.

These data are used in the USBM-developed CMRR to estimate roof strength. Average unit ratings have been calculated from both underground exposures and rock core. Anisotropy of roof rocks often can explain relative susceptibility to horizontal stress and this property has been provided for the range of common roof rocks. The data demonstrate that point load testing can provide an accurate, inexpensive method of obtaining a continuous strength record of bolted roof. This record will then form the basis of roof characterization for hazard assessment.

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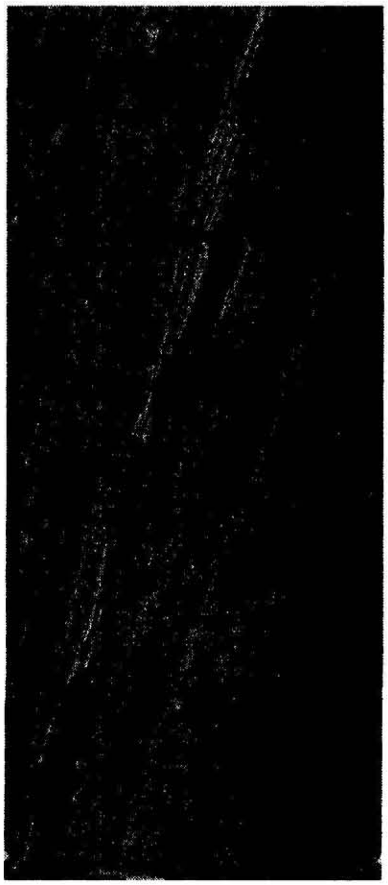
APPENDIX.—CORE GUIDE

The following pictorial guide is a combination of the pictorial core guide for the Pittsburgh Basin and the physical properties data measured for each rock type. These data are presented for selected rock types that represent the most common coal mine roof rocks. A complete data summary is available for most rocks, but some data are omitted where unavailable.

The following data are based upon work done by John C. Ferm. His consent to the use of his photographs is gratefully acknowledged.

Unit rating = 35

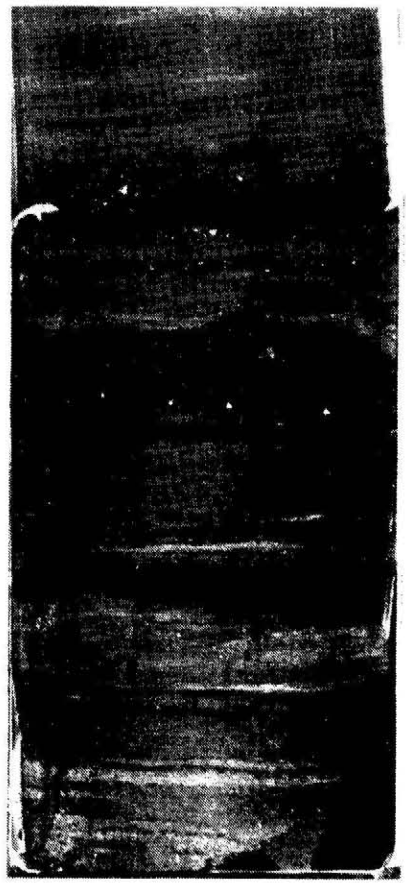


Slumped Sandy Shale
(014)

Unit rating = 35

Axial strength = 4,870 psi

Diametral strength = 790 psi

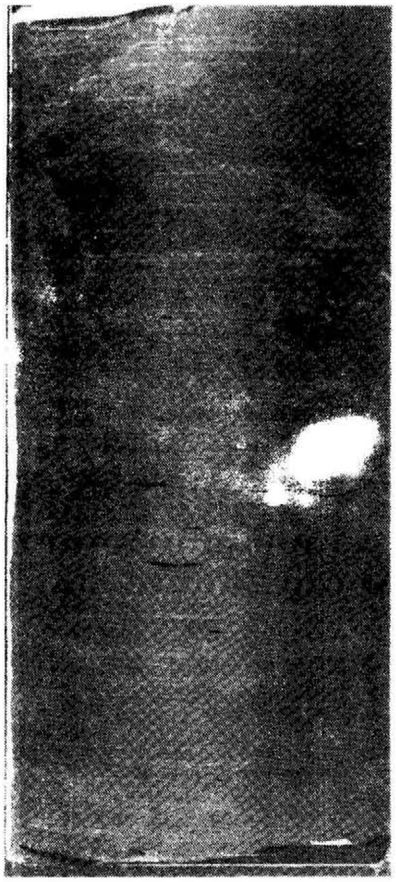


Black Shale with Coal Streaks
(113)

Unit rating = 39

Axial strength = 6,367 psi

Diametral strength = 1,512 psi

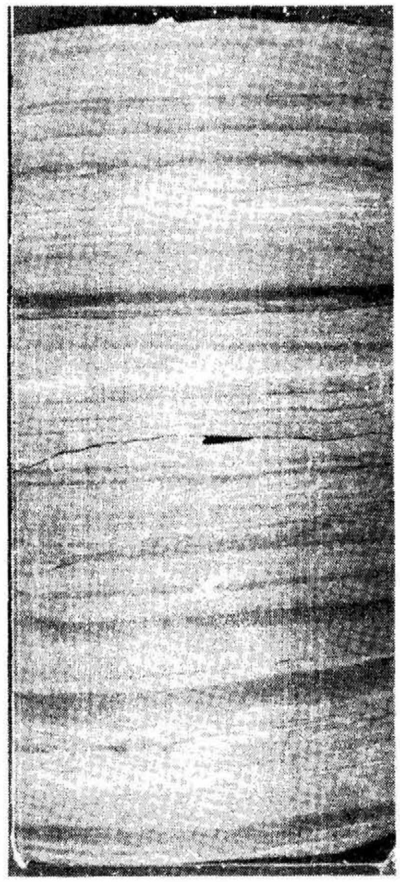


Black Shale
(114)

Unit rating = 45

Axial strength = 7,770 psi

Diametral strength = 3,628 psi

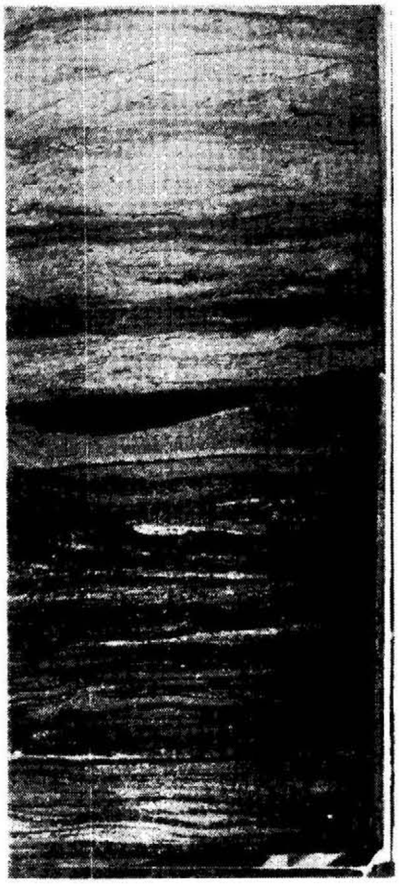


Dark Gray Layered Shale
(122)

Unit rating = 33

Axial strength = 5,237 psi

Diametral strength = 1,299 psi

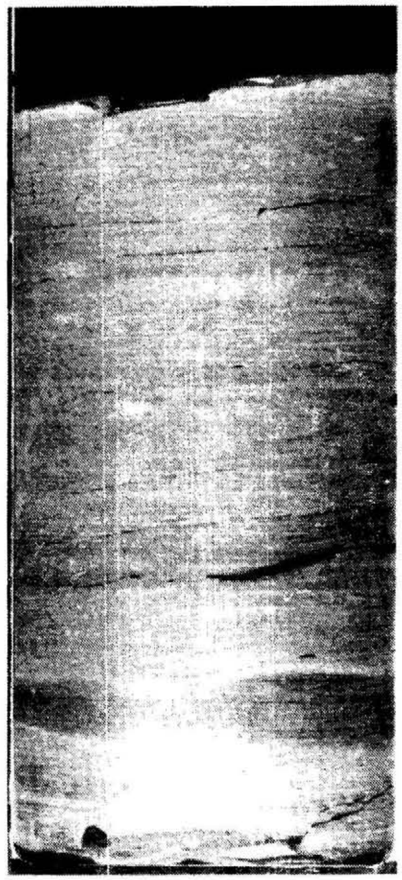


Dark Gray Shale with Coal Streaks
(123)

Unit rating = 36

Axial strength = 5,196 psi

Diametral strength = 1,148 psi



Dark Gray Shale
(124)

Unit rating = 29

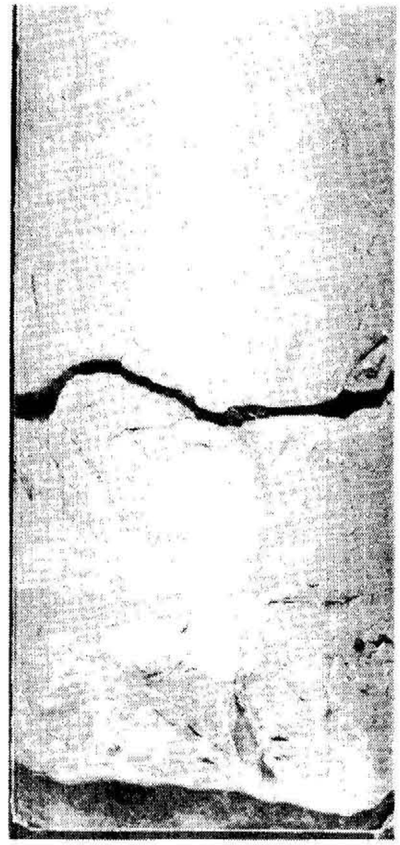
Diametral strength = 1,284 psi

Dark Gray Fireclay
(127)

Unit rating = 28

Axial strength = 4,719 psi

Diametral strength = 920 psi



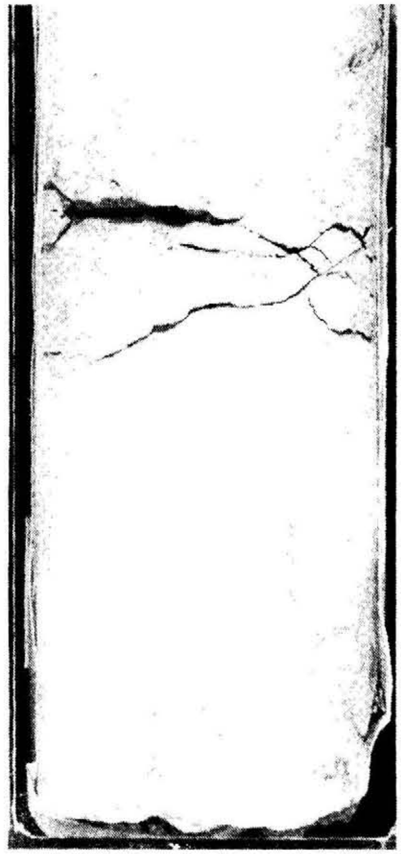
Light Gray Green Fireclay
(137)

Unit rating = 30

Axial strength = 9,329 psi

Diametral strength = 2,319 psi

Green Claystone
(147)



Light Gray Green Fireclay
with Limestone Nodules
(237)

Unit rating = 48

Axial strength = 11,335 psi

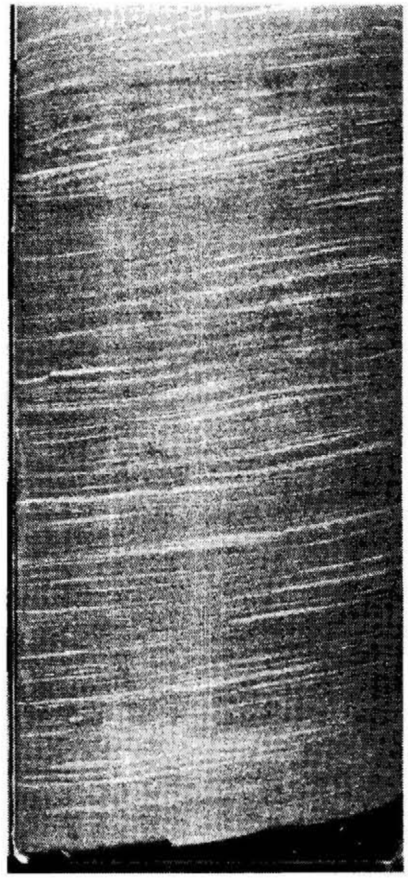
Diametral strength = 2,508 psi

Dark Gray Shale and
Interbedded Sandstone
(322)

Unit rating = 40

Axial strength = 6,990 psi

Diametral strength = 1,548 psi

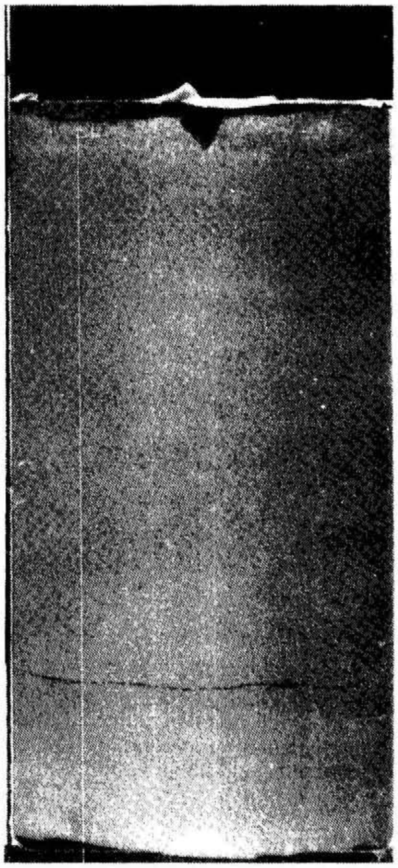


Dark Gray Shale with
Sandstone Streaks
(323)

Unit rating = 47

Axial strength = 7,980 psi

Diametral strength = 1,344 psi



Dark Gray Massive Sandy Shale
(324)

Unit rating = 48

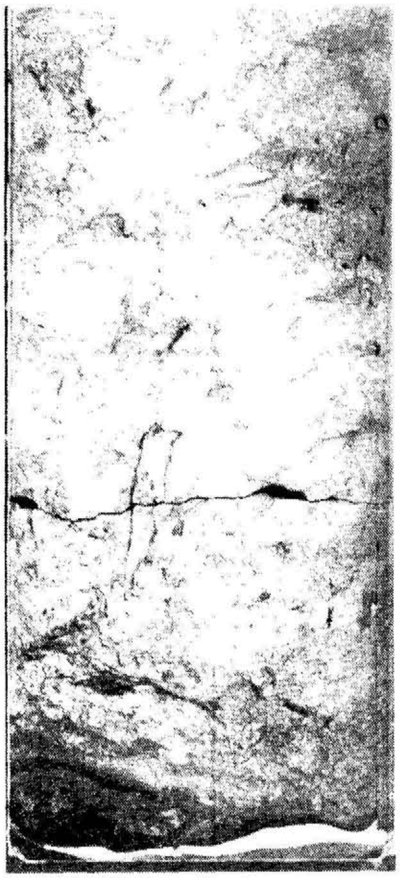
Axial strength = 6,063 psi

Diametral strength = 1,914 psi

Dark Gray Massive Churned Sandy Shale
(325)

Unit rating = 29

Axial strength = 1,253 psi

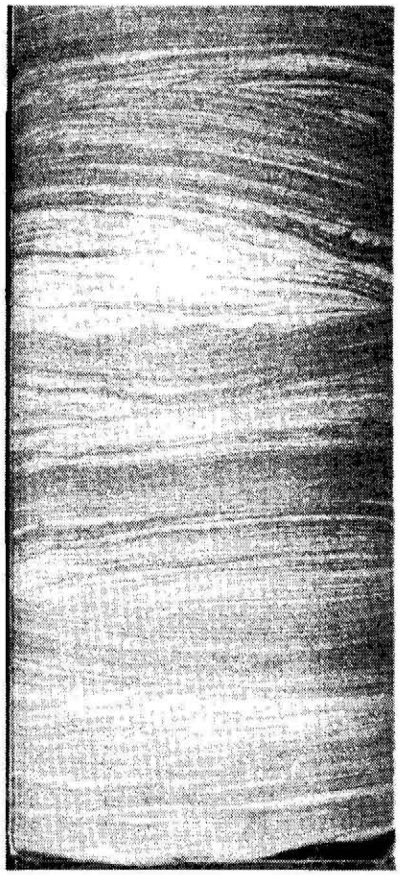


Dark Gray Sandy Fireclay
(327)

Unit rating = 45

Axial strength = 4,653 psi

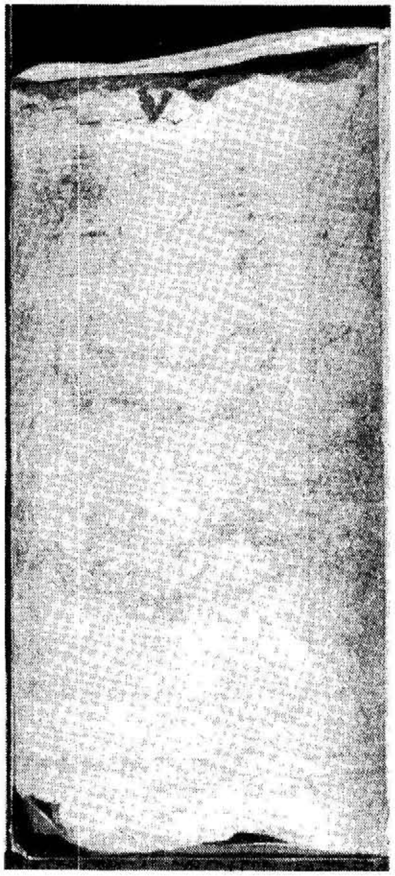
Diametral strength = 1,482 psi



Light Gray Green Shale
and Interbedded Sandstone
(332)

Axial strength = 5,953

Diametral strength = 5,660 psi



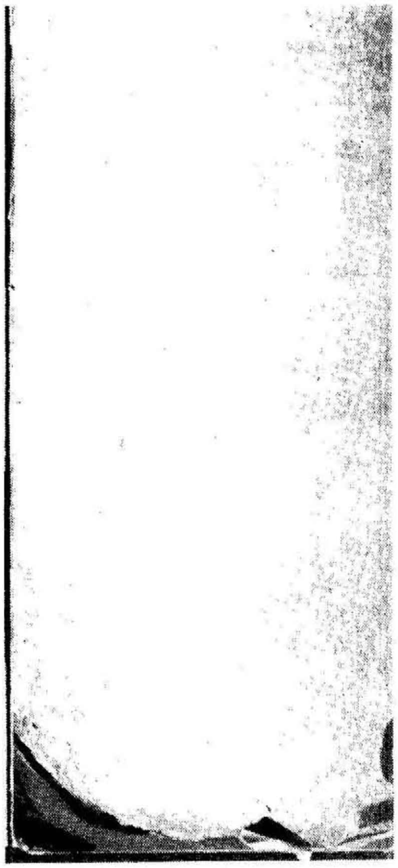
Light Gray Green Sandy Fireclay (337)

Axial strength = 9,297 psi

Red and Green Sandy Claystone (357)

Axial strength = 1,786 psi

Diametral strength = 707 psi

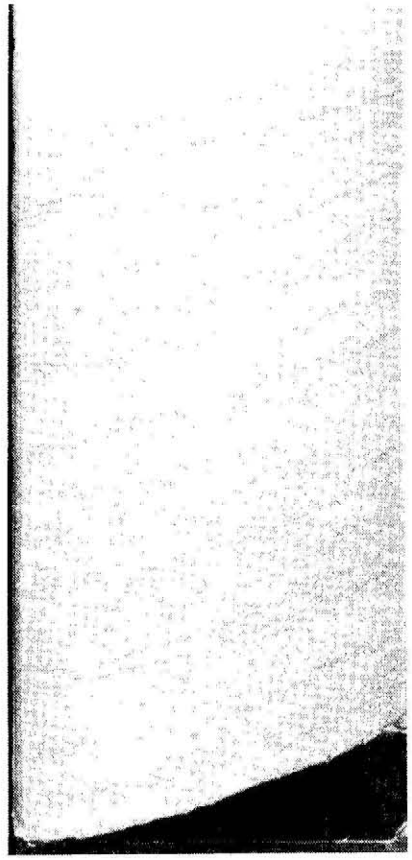


Light Gray Green Sandy Fireclay
with Limestone Nodules
(437)

Unit rating = 63

Axial strength = 8,886 psi

Diametral strength = 3,552 psi

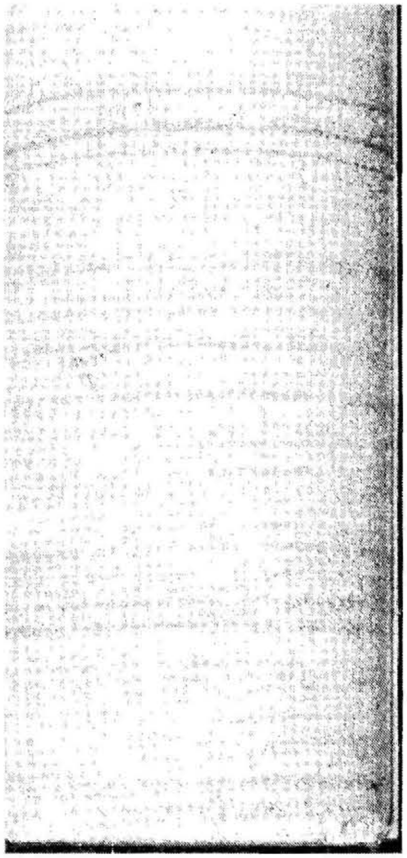


Gray Crossbedded Sandstone
(541)

Unit rating = 63

Axial strength = 11,550 psi

Diametral strength = 4,129 psi

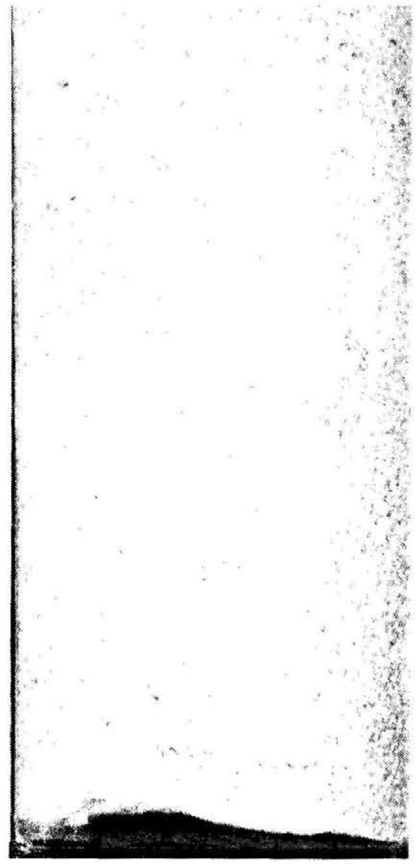


Gray Sandstone with
Shale Streaks, Flat
(543) FLT

Unit rating = 77

Axial strength = 10,876 psi

Diametral strength = 13,632 psi

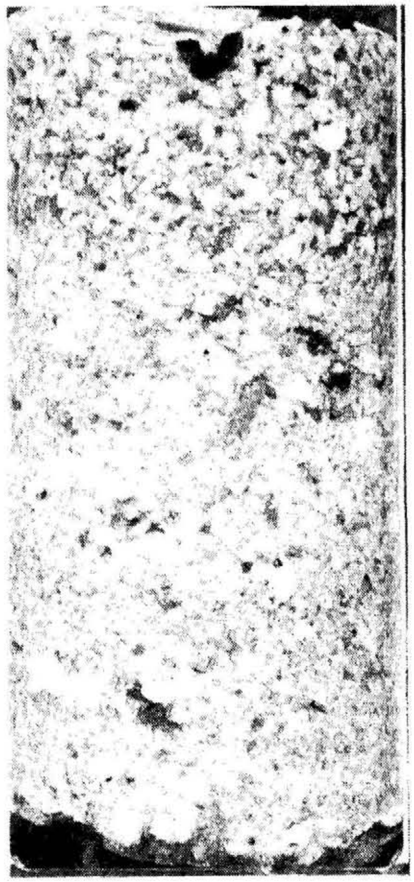


Gray Massive Sandstone
(544)

Unit rating = 43

Gray Sandstone with Coal Spars
(749)

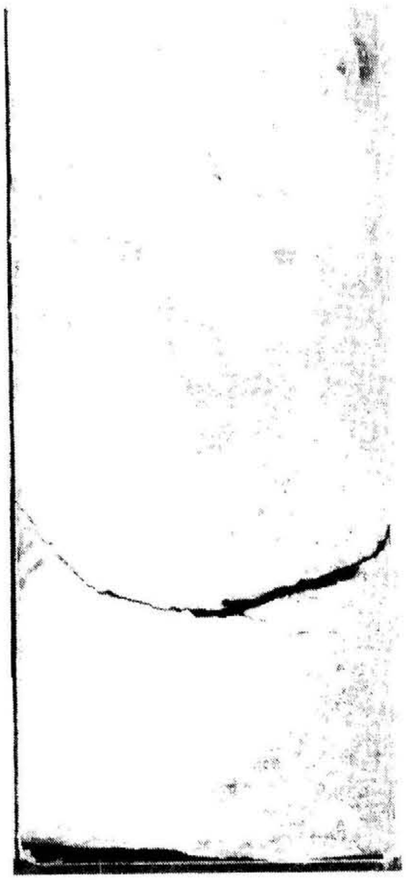
Unit rating = 46



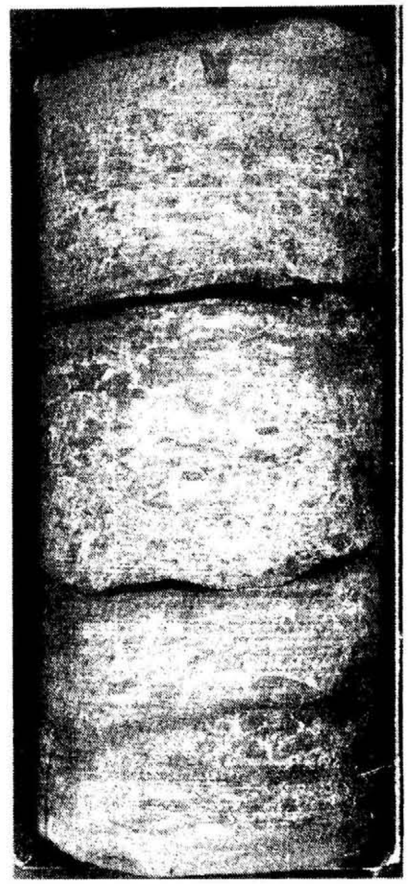
Hard Quartz Pebble
Conglomerate
(764)

Unit rating = 78

Axial strength = 3,231 psi



Shale Breccia
(772)

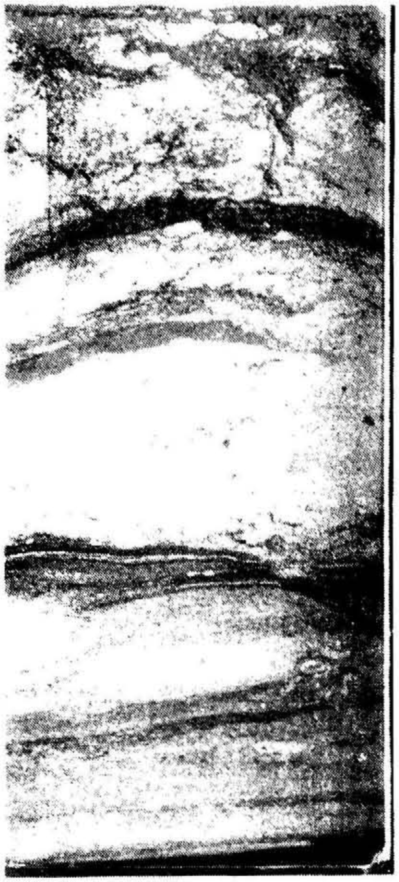


Shale Pebble Shaley
Limestone Breccia
(782)

Unit rating = 63

Diametral strength = 2,130 psi

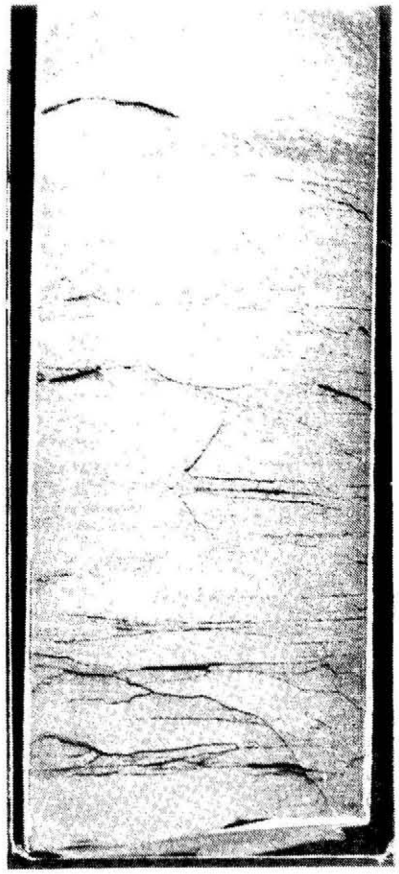
Axial strength = 11,386 psi



Layered Fine Grained Shaley Limestone
(802)

Diametral strength = 5,889 psi

Axial strength = 8,884 psi



Massive Fine Grained Shaley Limestone
(804)

Unit rating = 35

Axial strength = 4,305 psi

Diametral strength = 2,018 psi

Massive Fine Grained Shaley Limestone with Fossil Shells (894)

Axial strength = 5,684 psi

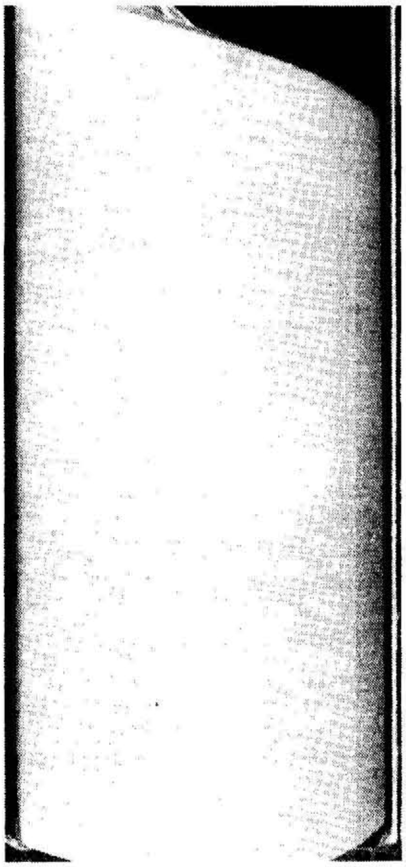
Diametral strength = 1,300 psi

Fine Grained Shaley Limestone with Limestone Nodules and Fossil Shells (896)

Unit rating = 100

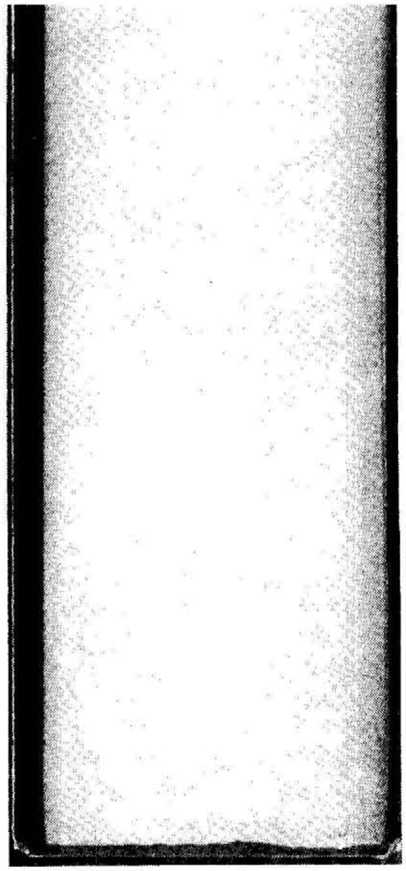
Axial strength = 18,203 psi

Diametral strength = 18,397 psi



Massive Fine Grained Limestone
(904)

Unit rating = 94



Nodular Fine Grained
Limestone
(906)

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