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MEASUREMENT OF ELASTIC WAVE VELOCITIES IN COAL SAMPLES OF DIFFERENT RANK

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ABSTRACT

Laboratory experiment were carried out to measure: 1)compression (Vp) and shear wave (Vs) velocities in coal samples with different ranks (or vitrinite reflectance) from low rank to high rank coal, and 2) to measure Vp and Vs on coal under different fluid saturation conditions including methane and water. The coal samples were subjected to a range of confining pressures and pore pressures that resulted in effective pressures in the range 0 to 3000 psi. Measurements were performed on: 1) fresh coal samples, under gas pore pressure 2) dry samples under gas pore pressure, and 3) water-saturated samples, under water pore pressure. The gas used to pressurize the pore system was methane. Coal samples used in the experiments were: Four samples with vitrinite reflectance values (Ro) between 0.7 and 1.52%, from the Bogotá Basin, and two low rank samples (with Ro < 0.5%) from the Powder River, and Washakie basins of Wyoming. The acoustic experiments on coal indicate that both compressional and shear wave velocities (Vp and Vs) are very sensitive to effective pressure, increasing with it. Most of the samples show a clear trend of increases for Vp with effective pressure. Also, the Vp velocity increases with pore pressure, and become less sensible to effective pressure. The shear wave velocity also increases with effective pressure; however, Vs velocity does not show a clear trend with pore pressure. It was observed that both Vp and Vs velocities increase with coal rank (vitrinite reflectance), where the low rank coal shows lower velocities than the higher rank coal. This trend is related also to coal porosity. Our experiments should be useful indicators of the saturation stage in coalbed methane exploration. In addition these experimental data provide useful data for AVO (amplitude versus offset) modeling, and interpretation of seismic surveys carried out for coalbed Methane exploration.

Key words: compression wave velocity (Vp); shear wave velocities (Vs)

MEDICIONES DE LAS VELOCIDADES ELÁSTICAS DE CARBONES DE DIFERENTES RANGOS

RESUMEN

Pruebas de laboratorio fueron empleadas para: 1) medir las velocidades de compresión (Vp) y velocidades de corte (Vs) en muestras de carbón de diferentes rangos (o con diferentes valores de reflectancia de vitrinita) y 2) medir las velocidades de Vp y Vs en los carbones bajo diferentes condiciones de saturación de fluidos incluyendo agua y gas metano. Las variaciones de Vp y Vs se estudiaron en relación a las variaciones de las presiones de confinamiento y de poro en un rango de 0 a 3000 psi. Las pruebas fueron realizadas empleando: 1) muestras frescas de carbón (con la humedad natural de carbón) bajo presión de poro con gas, 2) Muestras de carbón secas bajo presión de poro con gas, y 3) Muestras de carbón saturadas en agua, bajo presión de poro con agua. El gas empleado para presurizar los poros del sistema fue metano. Las muestras de carbón empleadas en las pruebas fueron: cuatro muestras de carbón de la cuenca de Bogotá con reflectancia de vitrinita (Ro) entre 0.7 y 1.52%, y dos muestras de carbón de bajo rango (con Ro < 0.5%) de las Cuencas Powder River y Washakie de Wyoming. Los experimentos acústicos en los carbones indican que las velocidades de compresión y de corte (Vp y Vs) son muy sensitivas a la presión efectiva, incrementándose Vp y Vs con el aumento de la presión efectiva de confinamiento.La mayoría de las muestras de carbón muestran una tendencia clara de incremento de Vp con el aumento de la presión efectiva. La velocidad Vp se incrementa con la presión de poro haciéndose menos sensitiva a la presión efectiva. La velocidad de corte (Vs) también se incrementa con la presión efectiva, sin embargo la velocidad Vs no muestra una tendencia clara con respecto a la presión de poro. Se observo que las velocidades Vp y Vs se incrementan con el rango del carbón (con el incremento de Ro), en donde el incremento de las velocidades Vp y Vs coincide con el incremento del rango de los carbones. Esta tendencia en las velocidades Vp y Vs también esta influenciada con la porosidad de la muestra de carbón. Los resultados de las experiencias pueden ser empleadas para la exploración por métodos sísmicos de yacimientos de gas asociado a carbón. Adicionalmente estos resultados son útiles para los análisis de AVO (amplitud versus distancia) así como también para en la interpretación sísmica.

Palabras claves: Velocidad de compresión onda de (Vp), velocidad de corte de onda (Vs); rangos de carbón; reflectancia de vitrinita (Ro).

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INTRODUCTION

Since coals are characterized by their great capacity to absorb gases through their high microscopic porosity and molecular structures; it is reasonable to determine the relationship between the gas content of coal seams at different coal ranks and confining at different confining pressure. The results of this research could be used for AVO analysis in coalbed methane exploration so that gas-saturated coal seams can be detected with seismic methods.

The purposes of this research were: 1) to measure compression (Vp) and shear wave (Vs) velocities in coal samples with different ranks (or vitrinite reflectance) from low rank to high rank coal, 2) to measure Vp and Vs on coal under different fluid saturation conditions including gas, and water. The coal samples were subjected to a range of confining pressures and pore pressures resulting in effective pressures from 0 to 3000 psi.

Measurements were performed primarily on fresh samples that were partially saturated with water and gas. The gas used to pressurize the pore system was methane. Coal samples were subjected to the methane pore system pressure for approximately 48 hours before measurements were commenced, in order to obtain good gas saturation. Companion samples were taken to obtain both vertical and horizontal orientations, i.e. perpendicular and parallel to the bedding to study anisotropy.

Additional velocity measurements were made on the lowest and highest rank coal samples, using dry and water-saturated samples under methane and water pore pressures respectively.

COAL SAMPLES

The purpose of the coal-sampling program was to obtain fresh coal samples that were representative of coalbed methane reservoir conditions, in terms of coal moisture and some gas content.

Since coalbed methane reservoirs exist in coal with vitrinite reflectance (Ro) from 0.4 to 1.5%, the objective of the sampling program was to obtain coal samples within this range of vitrinite reflectance. A total of 6 samples were used for the geophysical experiments. Four samples, from the Guaduas Formation in the Bogotá Basin, Colombia, were obtained from underground coal mines, with Ro values between 0.7 and 1.52%. Two low rank samples of the Fort Union Formation (with Ro < 0.5%) were obtained from the Powder River (PRB), and Washakie (Wash) basins of Wyoming, USA.

Coal ranks or maturation stages of the coal samples used for the geophysics experiments were characterized using different techniques including: vitrinite reflectance, proximate, and Rock Eval analyses. Results are listed in TABLES 1, 2 and 3.

The results illustrate how fixed carbon increases with vitrinite reflectance and rank as expected, at the same time that the volatile matter content diminishes. The ash content is lower than 4% in the coal samples from the Bogotá Basin. The Fort Union coal samples exhibit an ash content of more than twice that of the Bogotá Basin coals.

The Rock Eval analyses were the third method used in this study to determine the maturation of the coal samples and to characterize the gas generation potential of these coal samples. As in the previous analyses, the Rock Eval results agree with the vitrinite reflectance data and the proximate analysis. TOC increases with maturity and vitrinite reflectance; also the Tmax parameter follows the same trend indicated by the vitrinite reflectance, porosity and density measurements

Porosity, matrix density, and bulk density of the coal samples were determined by Archimedes' method, which weighs the sample in the following conditions: 1) dry-sample in air, 2) liquid-saturated-sample in air, and 3) liquid-saturated in the liquid. Then the volume of each sample and the differences in weights were used to calculate porosity, matrix density and bulk density.

When the coal samples were cored, there was indication that most of the coals might not be water wet. For this reason, isopropyl alcohol was used as the pore saturant instead of water, in order to obtain good pore saturation. Drying of the core was done at 60 ºC (140 ºF) for approximately 24 hours. TABLE 4 reports the values obtained for porosity, matrix density, and bulk density.

Different density and porosity values are observed on perpendicular and parallel plugs from the same sample. This is due to the lamination nature of the coals, which increases the parallel porosity of the coal. Only the Trinidad sample presents higher perpendicular porosity than parallel porosity.

Density and porosity are difficult to determine in coals due to the presence of micro pores not accessible by the saturant liquid. Also the coal micro pores and micro fractures are filled up with waxes and/or gases. The

TABLE 1. Vitrinite reflectance Ro of coal samples.

Sample	Basin	Ro mean	Ro min	Ro max	St Dev
		(%)	(%)	(%)	
Fort Union	PRB	0.41	0.35	0.49	0.03
Fort Union	Washakie	0.45	0.41	0.51	0.03
El Convenio	Bogotá	0.79	0.68	0.90	0.05
La Trinidad	Bogotá	0.82	0.72	0.97	0.05
El Roble	Bogotá	1.22	1.01	1.52	0.09
La Cisquera	Bogotá	1.52	1.35	1.76	0.09

TABLE 2. Proximate analysis of coal sample.

Sample	Basin	Ro mean	Ash	Volatile M	Fixed C
		%	%	%	%
Fort Union	PRB	0.41	8.89	38.37	52.74
Fort Union	Washakie	0.45	8.58	33.27	58.15
El Convenio	Bogotá	0.79	2.95	31.83	65.22
La Trinidad	Bogotá	0.82	3.71	29.55	66.74
EL Roble	Bogotá	1.22	3.53	21.05	75.42
La Cisquera	Bogotá	1.52	1.81	16.7	81.49

minute nature of pores in the coal, give anomalously low porosity values when the liquid saturation is not properly done. The results obtained for both density and porosity are similar to data published by Levine (1993), indicating that the coal samples were effectively saturated with our choice of isopropyl alcohol. Figure 1 illustrates the hyperbolic-like relationship between the porosity and the vitrinite reflectance; on the other hand the density and vitrinite reflectance show a somewhat irregularly decreasing trend as illustrated by FIGURE 2.

Sample Preparation

One-inch diameter plugs were cut from fresh coal samples perpendicular to and parallel to the bedding. Fresh water was used as drilling fluid. Sample ends were ground flat and parallel on a diamond lap wheel. The prepared samples were kept in containers with fresh water until they were mounted in the pressure vessel for velocity measurement.

Methodology

We measure compression Vp and shear wave velocities Vs through cylindrical samples by placing transducer posts at each end of the sample. One transducer post serves as a transmitter and the other as a receiver (see FIGURE 3). The posts may be selectively operated in either compression or shear mode. The sample and transducer posts are encapsulated within vinyl tubing to isolate the sample and its pore system from the oil that is used to provide hydrostatic confining pressure on the sample and posts in the pressure vessel.

FIGURE 3 illustrates the electronic system to measure velocities; a pulse of voltage is applied to the transmitter transducer that causes the transducer post to distort. The distortion propagates through the transducer post, the sample, and the receiver transducer post and transducer. The receiver transducer generates a voltage when it is distorted. Wave velocity is determined as the ratio of sample length to wave travel time through the sample. Total travel time of the wave is measured, including travel time through the transducer posts and sample. Travel time through the sample is determined by subtracting transducer post travel times from the total wave travel time. Transducer post travel times are determined with no sample between the posts.

FIGURE 4 shows a sample and the two transducer posts encased in a vinyl sleeve. Hydraulic access lines to the sample and electrical cable to the transducers are also visible. The whole assembly is suspended above the pressure vessel in which the velocity measurements are made. FIGURE 5 illustrates the pore pressure system, and FIGURE 6 illustrates the confining pressure system.

TABLE 3. Rock Eval analysis of coal samples.

Source Rock Analysis Rock Eval Pyrolysis											
Sample	Basin	S1	S2	Tmax	I-C	T-C	TOC	PI	HI	GP	Ro
		mg HC/g	mg HC/g	º C	%C	%C	%C	S1/(S1+S2)	S2/TOC	S1+S2	(%)
Fort Union	PRB	0.68	92.96	414	0.032	61.05	61.02	0.01	152	93.6	0.41
Fort Union	Washakie	0.11	107.26	403	0.072	66.34	66.27	0.00	162	107.4	0.45
El Convenio	Bogotá	4.63	217.24	441	0.017	85.63	85.61	0.02	254	221.9	0.79
La Trinidad	Bogotá	2.49	202.58	433	0.026	79.73	79.70	0.01	254	205.1	0.82
El Roble	Bogotá	4.28	142.37	469	0.017	88.02	88.00	0.03	162	146.7	1.22
La Cisquera	Bogotá	1.20	95.85	487	0.020	90.04	90.02	0.01	106	97.0	1.52

S1: hydrocarbons present in the sample, S2: hydrocarbon generated during pyrolysis, Tmax: temperature at the peak of hydrocarbons generation during pyrolysis, I-C: inorganic carbon content, T-C: total carbon content, TOC: total organic carbon content, PI: production index, HI: hydrogen index, GP: genetic potential of hydrocarbons, Ro: vitrinite reflectance.

TABLE 4. Coal porosity and density.

Sample	Ro	Porosity	Matrix Density	Bulk Density**
	(%)	(Fractional)	(g/cc)	(g/cc)
Fort Union-PRB (par)	0.41	0.395	1.480	1.291
Fort Union-PRB (perp)	0.41	0.388	1.465	1.284
Fort Union Wash (par)	0.45	0.242	1.481	1.365
Anadarko Wash (perp)	0.45	0.198	1.326	1.261
El Convenio (par)	0.78	0.028	1.262	1.255
El Convenio (perp)	0.78	0.018	1.309	1.303
La Trinidad (perp)	0.82	0.0074	1.282	1.280
La Trinidad (par)	0.82	0.0088	1.275	1.272
El Roble (par)	1.22	0.0097	1.330	1.326
El Roble (perp)	1.22	0.0036	1.334	1.333
La Cisquera 1 (par)	1.52	0.0119	1.307	1.304
La Cisquera 1 (perp)	1.52	0.0142	1.309	1.304

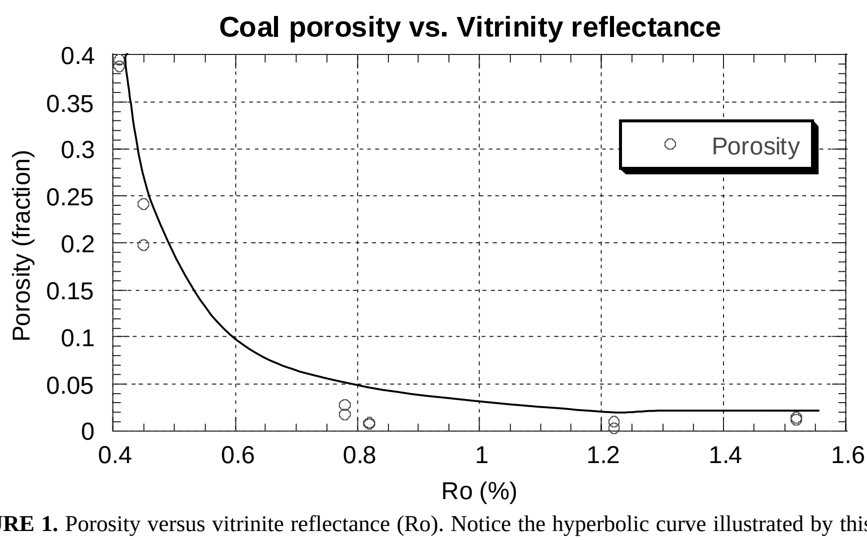

FIGURE 1. Porosity versus vitrinite reflectance (Ro). Notice the hyperbolic curve illustrated by this graph.

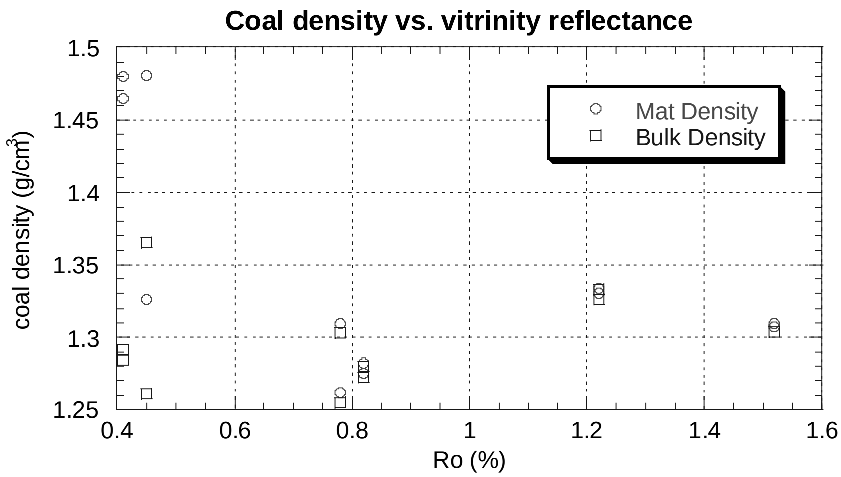

FIGURE 2. Density versus vitrinite reflectance (Ro). Matrix density o. Bulk density □. Notice that there is no clear trend in this figure.

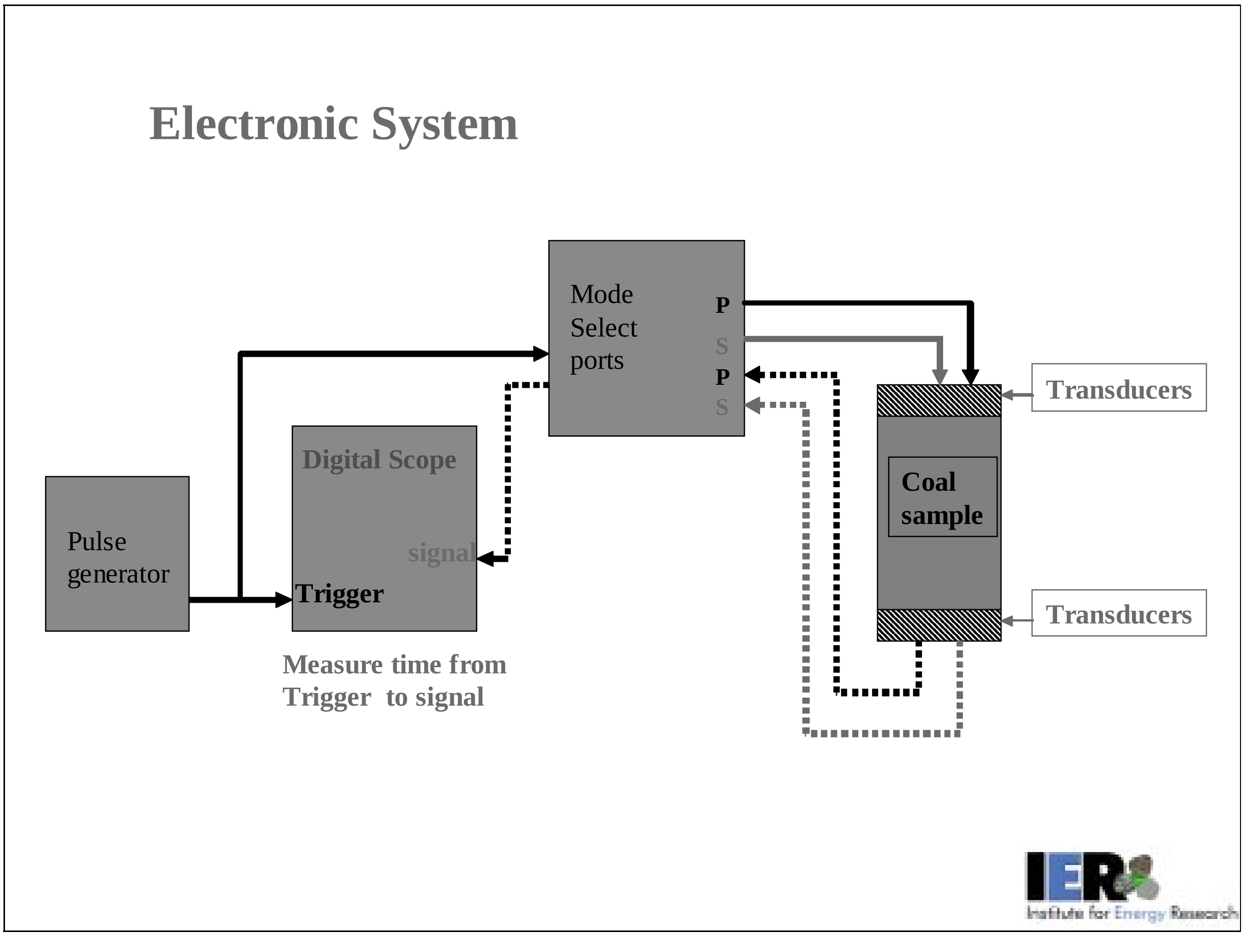

FIGURE 3. Schematic drawing of the electronic system used to generate pulses, and to measure Vp and Vs.

The measurement sequence for this set of samples was straightforward. Each fresh sample was mounted in the wave velocity apparatus and a set of measurements was run immediately for 0 psig pore pressure. The confining pressure was then raised to 2000 psig and methane injected into the pore system at 1500 psig. In order to obtain a good level of gas saturation, the pressure was kept for approximately 48 hours, after which another set of measurements was made. The confining pressure was then set to 3500 psig and the pore pressure elevated to 3000 psig. These pressures were maintained for approximately 48 hours, when another set of measurements was run.

The lowest and highest rank coal samples were dried at 60ºC for approximately 24 hours and another set of velocity measurements was run, with approximately 9 hours between runs.

These samples were then evacuated again, and saturated with tap water. In these experiences, water was injected into pore system. The high rank coal (Ro = 1.22%) survived well, but the low rank coal (Ro = 0.41%) disintegrated. For this reason, a taped up companion core was evacuated and then saturated successfully.

Dynamic Elastic Properties and Results

In addition to determining compression (Vp), and shear (Vs) wave velocities, the following dynamic properties were computed: compression and shear wave slowness (the reciprocal of velocity), shear modulus (μ), bulk modulus (K), Young's modulus (E), and Poisson's ratio (PR). Elastic theory for isotropic media indicates that any two elastic properties in addition to density can be used to define all of the elastic properties. The elastic moduli data presented in this report were computed assuming that coals were isotropic. Because Vp and Vs are functions of μ, K, and density, we are able to estimate the elastic moduli from the compression and sheaar wave velocities and the bulk density of samples.

Error Analysis

All of the results presented in this report concerning velocity, slowness, shear modulus, bulk modulus, Young's modulus, and Poisson's ratio depend on measurements of sample length, Vp and Vs total travel times through the system and sample, and travel times through the system with no sample. We estimate the likely range of error for each measurement and then determine how those errors affect each computed result. The range of the magnitude of expected errors for this data set is as follows.

Discussion

Both compressional and shear wave velocities increase with increasing effective pressure, this is due to the closure of the coal fractures. At 0 psi pore pressure Both Vp and Vs show a quick response to the effective pressure, as pore pressure is applied the velocity rise is less marked than at 0 pore pressure. FIGURES 7 to 12 illustrates the response of Vp and Vs for two coal samples, the Fort Union coal with a Ro of 0.41% and the El Roble coal with a Ro of 1.22%.

In fresh samples, the effects of gas pressure are seen most clearly in the compression wave Vp values. At high pressures the gas is less compressible than at low pressures, resulting in higher Vp velocities.

The shear wave velocities show no clear patterns, in both perpendicular and parallel plug samples, and show higher Vs at 0 psi pore pressure than at 3000 psi pore pressure. These effects can generally be observed in the graphs of compression and shear wave velocities for each of the fresh samples. In other words the Vs are generally very insensitive to the gas pressure.

A complete set of velocity measurements were performed for the El Roble coal sample (Ro = 1.22%) and for the Fort Union coal sample (Ro = 0.41%). These measurements were taken in the following conditions: 1) a fresh coal sample, which was partially saturated with water and gas, under gas pore pressure, 2) a dry coal sample under gas pore pressure, and 3) a water-saturated sample under water pore pressure.

In general, the results seem to be consistent with the idea that the compression wave velocity increases when the pores and fractures contain a stiffer pore fluid. Low-pressure gas has a small stiffness, i.e., it is very compressible, higher-pressure gas is less compressible and water has an even smaller compressibility, the former consideration is illustrated by the compressional wave velocity trends. The effect of the pore fluid compressibility on the shear wave velocity, however, is minimal.

The Fort Union coal sample, (with an Ro = 0.41%), shows a clear increasing trend of Vp with increasing effective and pore pressures, in which the dry-plug under gas pore pressure shows the lowest Vp velocity, and the water- saturated-plug under water pore pressure shows the highest Vp velocity. The fresh sample shows intermediate Vp values.

The El Roble coal sample, (with a Ro = 1.22%), shows minimal differences of Vp velocities among the three experimental conditions. In fact the difference between the highest and the lowest Vp values represent only 1.5%. This small difference is trivial since the error values of these test varies between 1.27 and 2.3%. This situation is explained by the extremely low porosity of this coal sample, which makes saturation very difficult, either with water or methane.

The coal plugs parallel to coal bedding always show higher velocities for both Vp and Vs than the coal plugs perpendicular to bedding. Velocities are between 1 and 5% higher on the parallel plugs than the perpendicular plugs. Yu, et al., (1993), report similar results.

To better resolve the question of how the presence of methane gas affects Vp and Vs velocities, more comparative measurement data are needed, especially for low rank coals.

Simulation of coalbed reservoir conditions in laboratory experiments

FIGURE 13 illustrates four-end member situations of coalbed reservoir phases whose description is as follows:

A. Gas-saturated coalbed under gas pore pressure. Hypothetically, the ideal situation consists of a dry coalbed methane reservoir in which the pore pressure is due only to gas. In this situation, pores and fractures are filled up with free gas. In addition, large quantities of both adsorbed and absorbed gas are present. Although dry CBM reservoirs are uncommon, examples are known in Arkoma Basin, where, according to Shirley (2000), some CMB wells produce zero water.

B. Water-saturated coalbed under water pore pressure. In a water-saturated coalbed, which is at the other end of the situational spectrum, the pore pressure is due to water. Many areas present coal seams with little or no gas, and these coal seams are totally water-saturated, including pores and fractures. One-hundred-percent waster-saturated coalbed reservoirs are also uncommon since coal gases are generated not only by thermogenic processes but also by biogenic processes. Therefore, some gas is present in the coalbed. However, for practical or economic purposes, many unsuccessful CBM wells can be considered 100% water-saturated.

C. Water-saturated coalbed under gas pore pressure. While indications of this hypothetical situation may be reproduced in the laboratory, such a CBM reservoir is unlikely to exist in nature, since the existence of a gas pore pressure implies that the coal seam was already gas-saturated.

D. Gas-saturated coalbed under water pore pressure. This fourth member situation consists of a coalbed with a porous space already saturated with gas under water pore pressure. This situation is probably the most realistic in nature, since most of the CBM reservoirs require dewatering before gas production can start. However, presently we are unable to reproduce this condition in the laboratory.

Thus our experiments have reproduced the coalbed methane conditions illustrated by figures 13. A, B, and C.

Yu, et. al. (1991, and 1993) measured Vp and Vs velocities on experiments. They used water-saturated coals under water pore pressure. Our experiment attempted to saturate the coals with gas in order to see the effect on Vp and Vs velocities. Presently we are not able to reproduce in the laboratory the CBM reservoirs conditions shown in FIGURE 13.D

In addition to the fluid and gases present in the CBM reservoirs, other factors affect the acoustic properties of coal beds: 1) coal anisotropy, 2) mineral or ash content in the coal, and 3) temperature of the CBM at depth.

(1) Our experiment indicates that the coal anisotropy is not important at the small scales of the samples, that is the coal plugs show low anisotropy effect for both Vp and Vs. However, at larger scale, coal seams are not as homogeneous as our coal samples used in the experiments. At outcrop scale, the coal bedding shows the alternation of bright and dull bands with different physical properties. One of the main factors that determine the anisotropy of coal seam is the nature of fractures and cleats.

(2) The mineral content greatly affects the coal density, since minerals have larger density than coaly matter. In addition to this effect, the mineral particles increase the porosity of coal by imprinting a heterogeneous characteristic to the coal matrix, which is different to the homogeneous matrix of the coal with no mineral content.

(3) Temperature is also another important parameter, since it will control the presence of liquid and gas

phases in coal beds. Also, it will control the precipitation of carbonates and other salts present in coalbed waters.

Conclusions

The acoustic experiments on coal indicate that both compressional and shear wave velocities (Vp and Vs) are very sensitive to effective pressure, that is, the larger the effective pressure, the faster the waves propagate.

At low confining pressure and zero pore pressure; there is a significant increment in both Vp and Vs velocities between 500 and 1000 psi of effective pressure (see FIGURES 7 through 12). This rapid rise in velocity is caused by the closure of micro-fractures or micro-cleats in the coal samples.

Most of the samples show a clear trend of increases for Vp with effective pressure. Also, the Vp velocity increases with pore pressure, and become less sensible to effective pressure, as indicated by the slope of the Vp curves at pore pressure > 500 psi.

The shear wave velocity also increases with effective pressure; however, Vs velocity does not show a clear trend with pore pressure. In fact, some coal samples exhibit higher Vs velocity at 0 pore pressure than at 3000 psi pore pressure.

Both Vp and Vs velocities are up to 5% higher in coal plugs parallel to bedding than plugs perpendicular to bedding. This demonstrates a low anisotropy of the coals at sample scale.

The Vp and Vs velocities of the El Roble coal (Ro = 1.22%) show little variation among the three experimental conditions. The highest Vp and Vs velocities were observed on the fresh coal sample under gas pore pressure. These values are close to the velocities obtained for the experiment run with a dry coal sample under gas pore pressure. On the other hand, the water-saturated sample under water pore pressure showed Vp and Vs velocities values lower than the previous experiments, but just in magnitude of 1 to 2 %. These results indicate the extreme low porosity of this coal sample, which makes it very difficult to saturate with water.

The low rank Fort Union coal sample (Ro = 0.41%) also presents some differences in Vp velocity related to the experimental conditions. The highest Vp obtained with the water-saturated sample under water pore pressure, shows a value of 8320 ft/sec at a pore pressure of 3000 psi. The lowest Vp value was obtained with the dry coal sample under gas pore pressure; in this case, the Vp was 7600 ft/sec at 3000-psi pore pressure. The fresh coal samples showed a Vp value of 7640 ft/sec at 3000-psi pore pressure. These results are explained if we consider that most of the pores and fractures in the water-saturated sample have been effectively saturated.

It was observed that both Vp and Vs velocities increase with coal rank (vitrinite reflectance), where the low rank coal shows lower velocities than the higher rank coal. This trend is related also to coal porosity. However, the presence of micro-fractures changes the bulk density as well as the porosity, and therefore low velocities could be recorded in a high rank coal with a high density of fractures.

FIGURE 4. Assembly of a coal sample in the vinyl sleeve, and transducers on both sides. Notice the tubes to apply pore pressure with methane. Also, a copper braid is observed on the side of the coal sample. This copper braid facilitates the gas saturation of the coal sample.

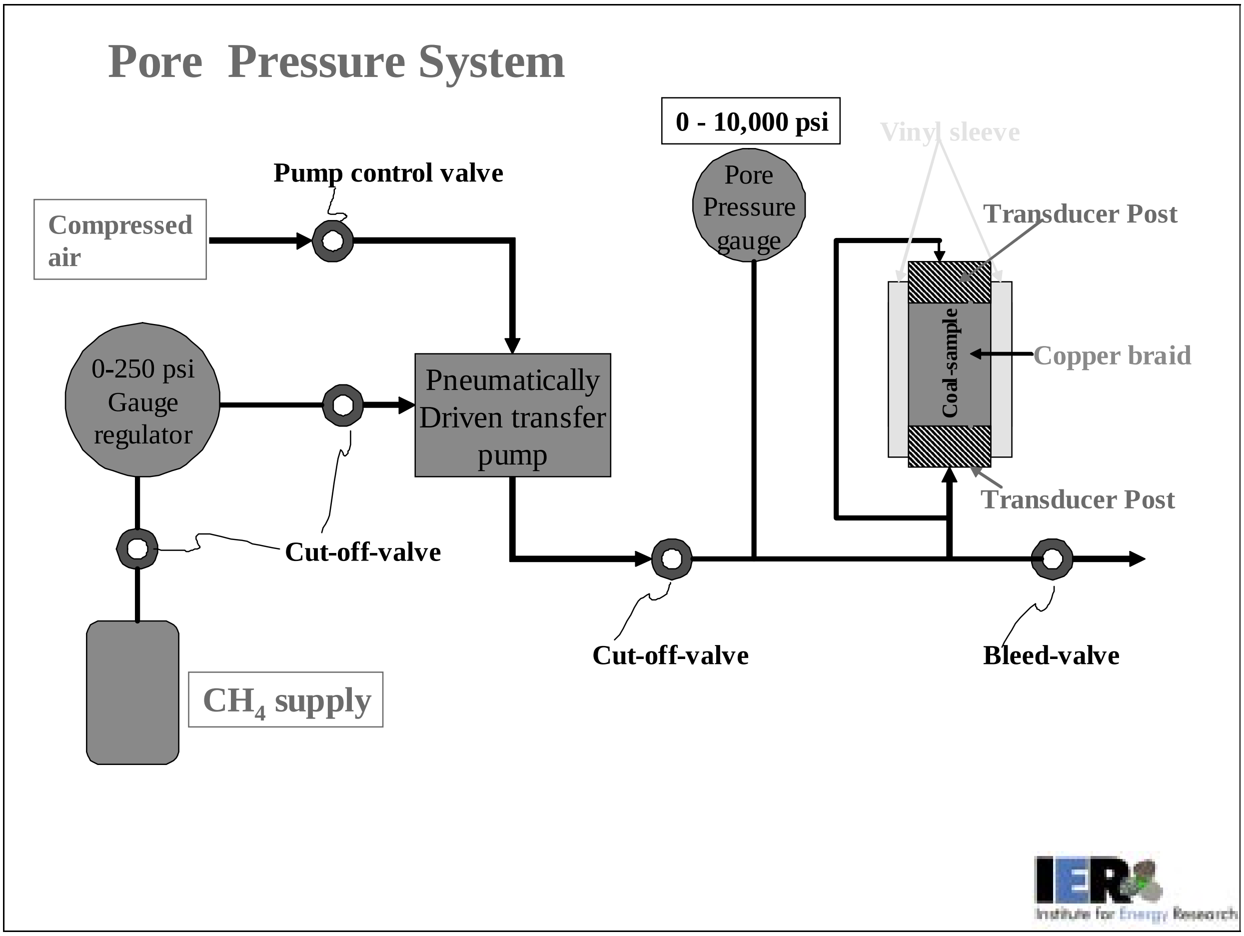

FIGURE 5. Schematic drawing of the pore pressure system used to saturate the coal samples with methane or water.

TABLE 5. Minimum and Maximum Expected Errors.

Property	Min Error %	Max Error %
Vp and dtp	0.924	2.36
	Anadarko (par) Fresh	Ft. Union 2 (perp) Dry
Vs and dts	0.752	2.1
	Anadarko (par) Fresh	Ft. Union 2 (perp) Dry
u	3.96	6.53
	Anadarko (par) Fresh	Ft. Union 2 (perp) Dry
K	5.06	6.53
	Anadarko (par) Fresh	Ft. Union 2 (perp) Dry
E	3.97	6.62
	Anadarko (par) Fresh	Ft. Union 2 (perp) Dry
PR	0.761	6.51
	Anadarko (par) Fresh	Ft. Union 2 (perp) Dry

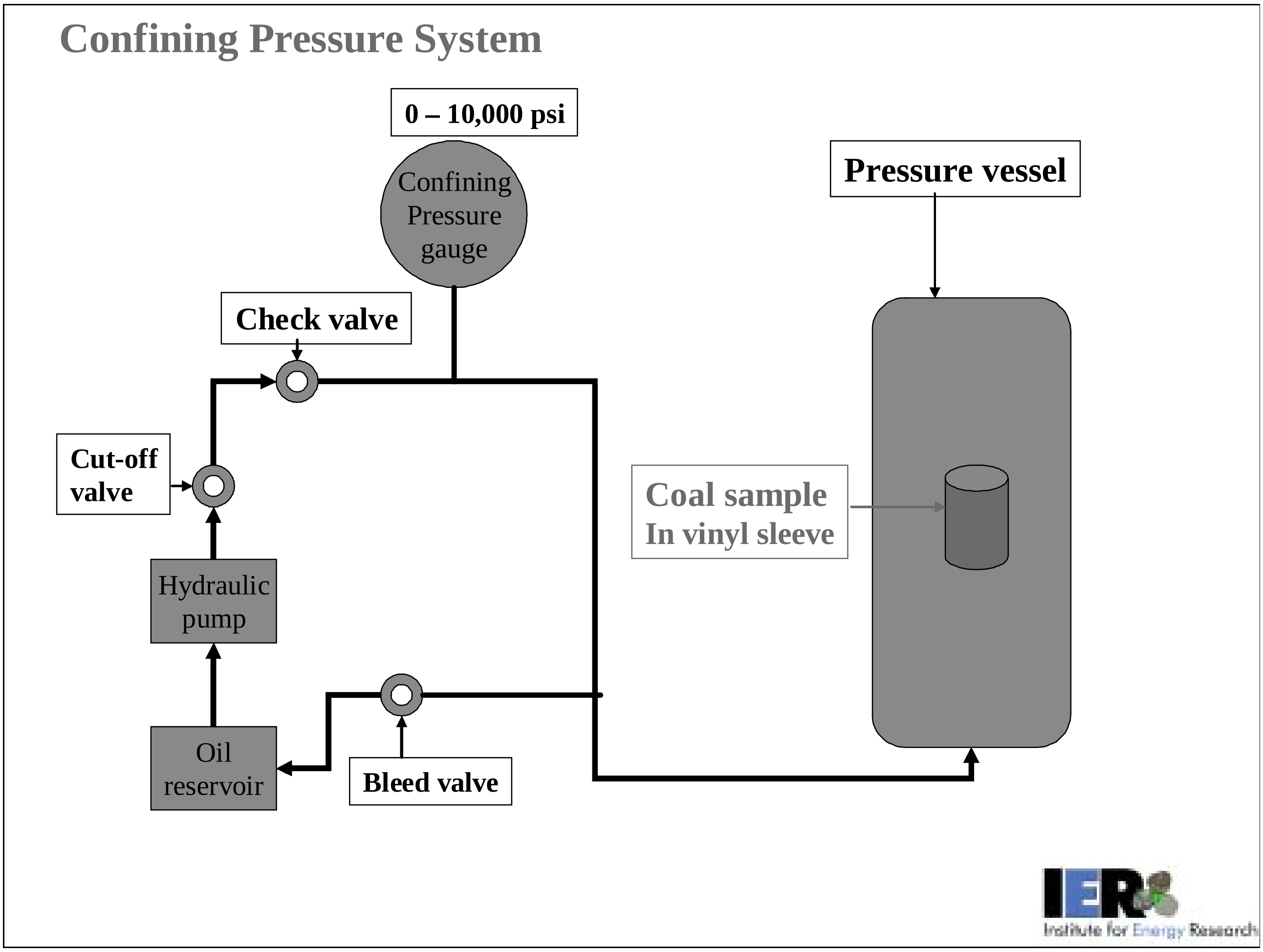

FIGURE 6. Schematic drawing of the confining pressure system. The coal sample along with the pore pressure system is placed in a cylinder (pressure vessel) filled up with oil, which is used to apply confining pressure in the coal sample.

In low rank coals Vp and Vs velocities are considerably different depending on the fluid present in the pores or fractures. The results indicate that the presence of water in the fractures will result in higher Vp and Vs velocities than those that would be measured in the presence of gas in the fractures.

Our experiments should be useful indicators of the saturation stage in coalbed methane exploration. In addition these experimental data provide useful data for AVO modeling, and interpretation of seismic surveys carried out for CBM exploration.

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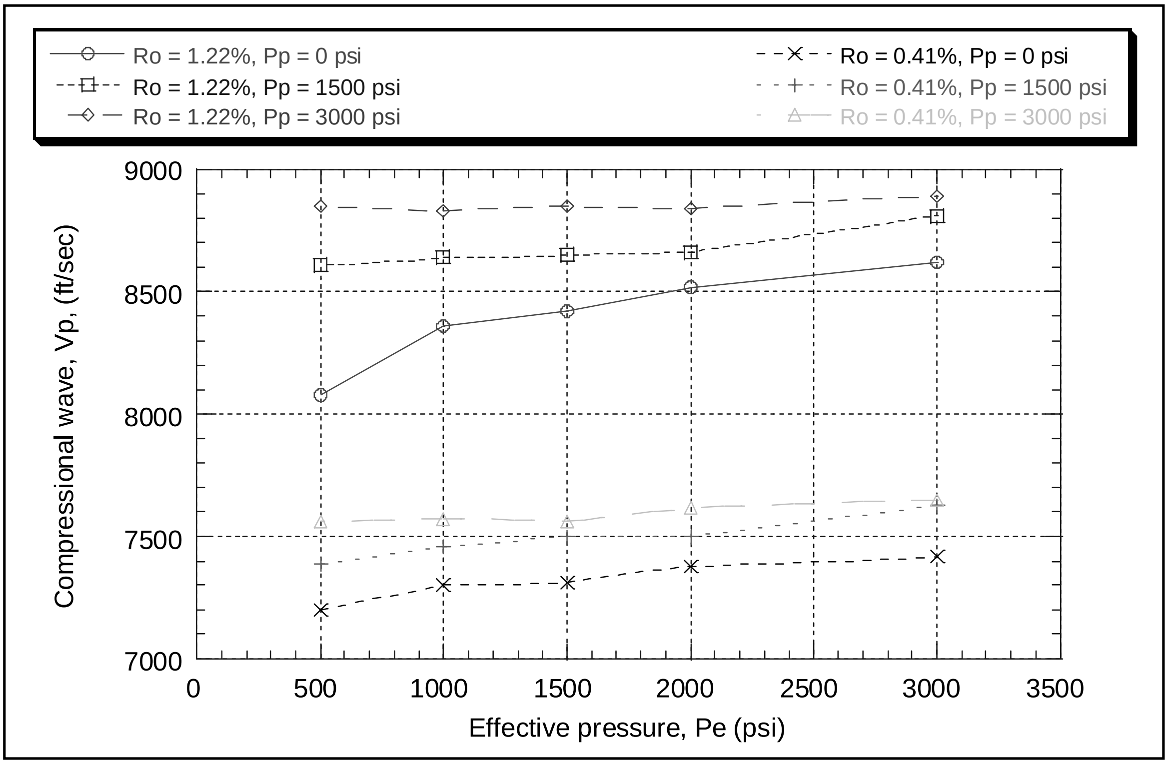

FIGURE 7. Fresh coal samples under methane pore pressure. Compressional wave velocity versus effective pressure of el Roble coal sample (Ro = 1.22%) and Fort union coal sample, Ro = 0.41%. The plot illustrates difference in Vp in perpendicular plugs from fresh coal samples. Conversion factors: 1ft/sec = 0.305 m/sec; 1 psi = 6.885 KPa)

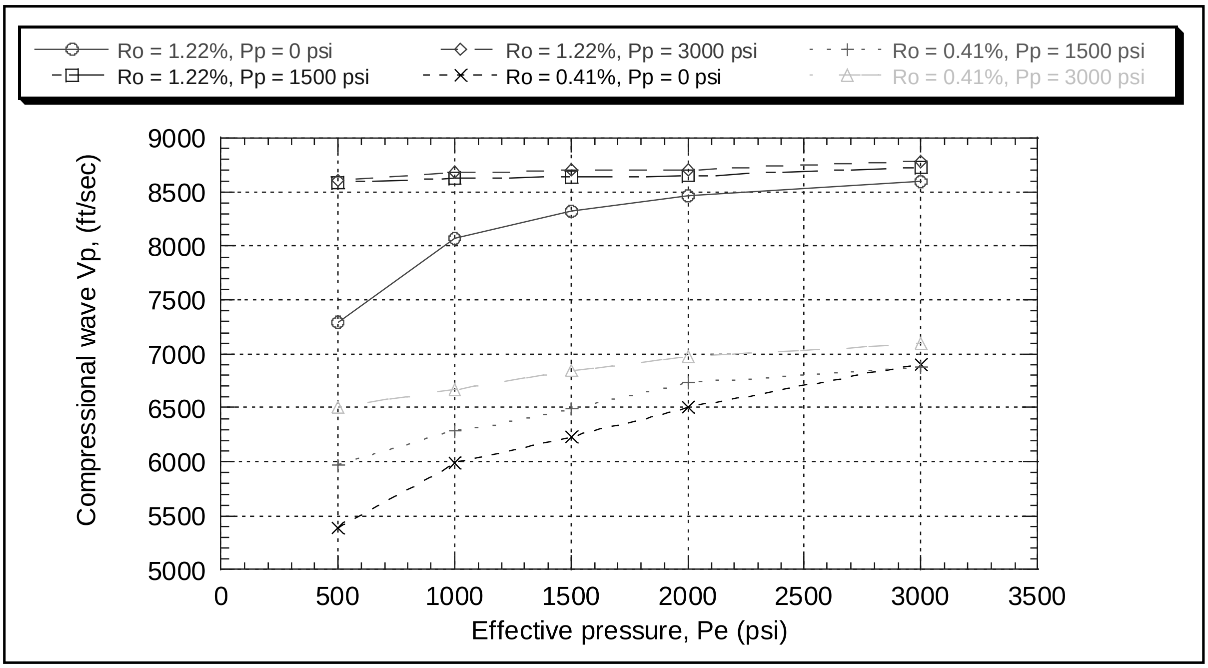

FIGURE 8. Dry coal samples, under methane pore pressure. Compressional wave velocity versus effective pressure for el Roble coal sample, (Ro = 1.22%), and Fort Union coal sample, Ro = 0.41%. The plot illustrates difference in Vp in perpendicular dried plugs. Conversion factors: 1ft/sec = 0.305 m/sec; 1 psi = 6.885 KPa.

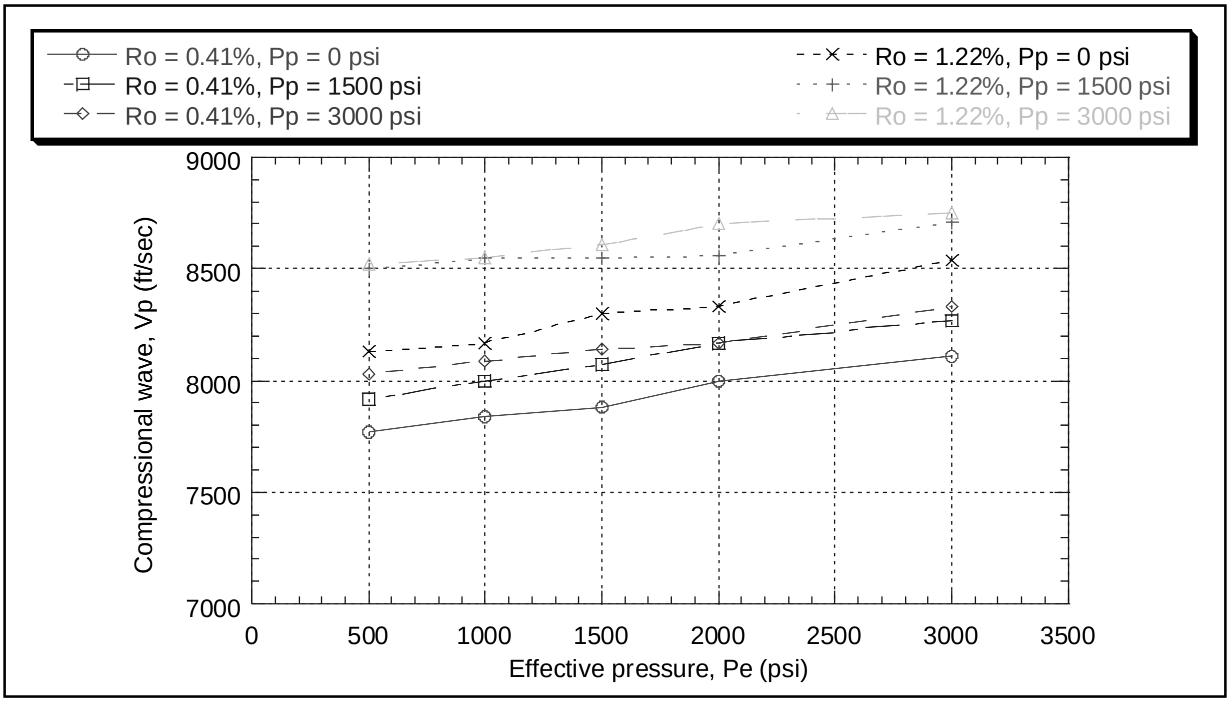

FIGURE 9. Water –saturated coal samples, under water pore pressure. Compressional wave velocity versus effective pressure for el Roble coal sample, (Ro = 1.22%), and Fort Union coal sample, Ro = 0.41%. The plot illustrates difference in Vp in perpendicular plug, and water-saturated. Conversion factors: 1ft/sec = 0.305 m/sec; 1 psi = 6.885 KPa.

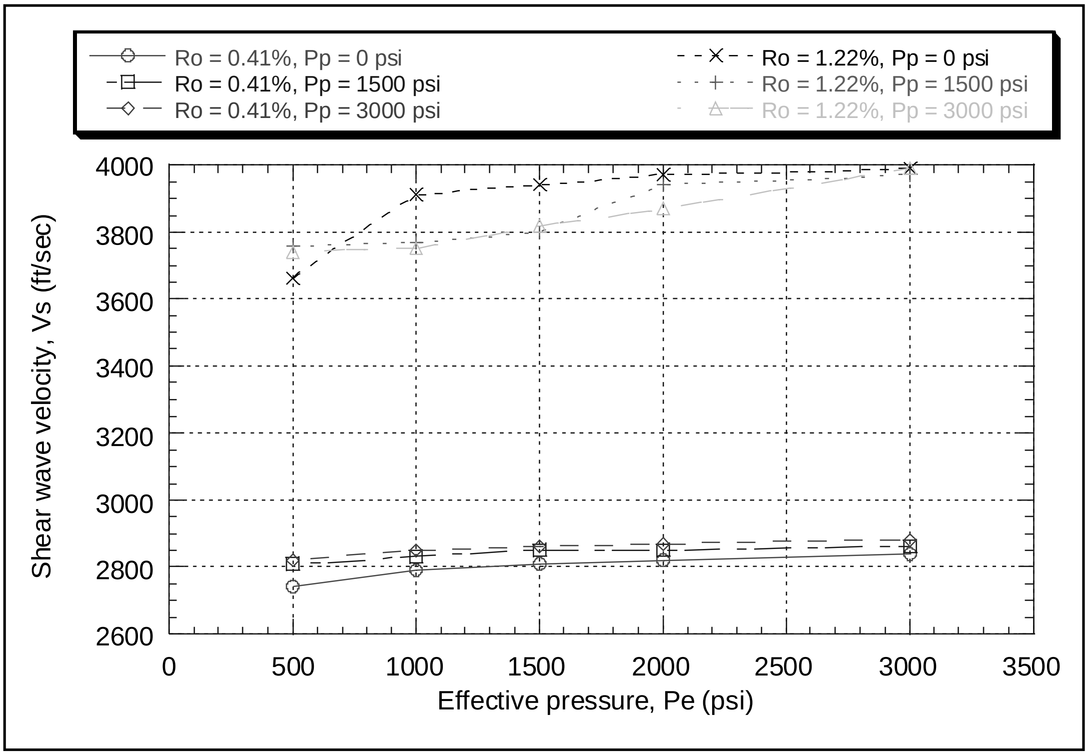

FIGURE 10. Fresh coal samples under methane pore pressure. Shear wave velocity versus effective pressure of el Roble coal sample, (Ro = 1.22%), and Fort union coal sample,(Ro = 0.41%). The plot illustrates difference in Vs in perpendicular plugs from fresh coal samples. Conversion factors: 1ft/sec = 0.305 m/sec; 1 psi = 6.885 KPa.

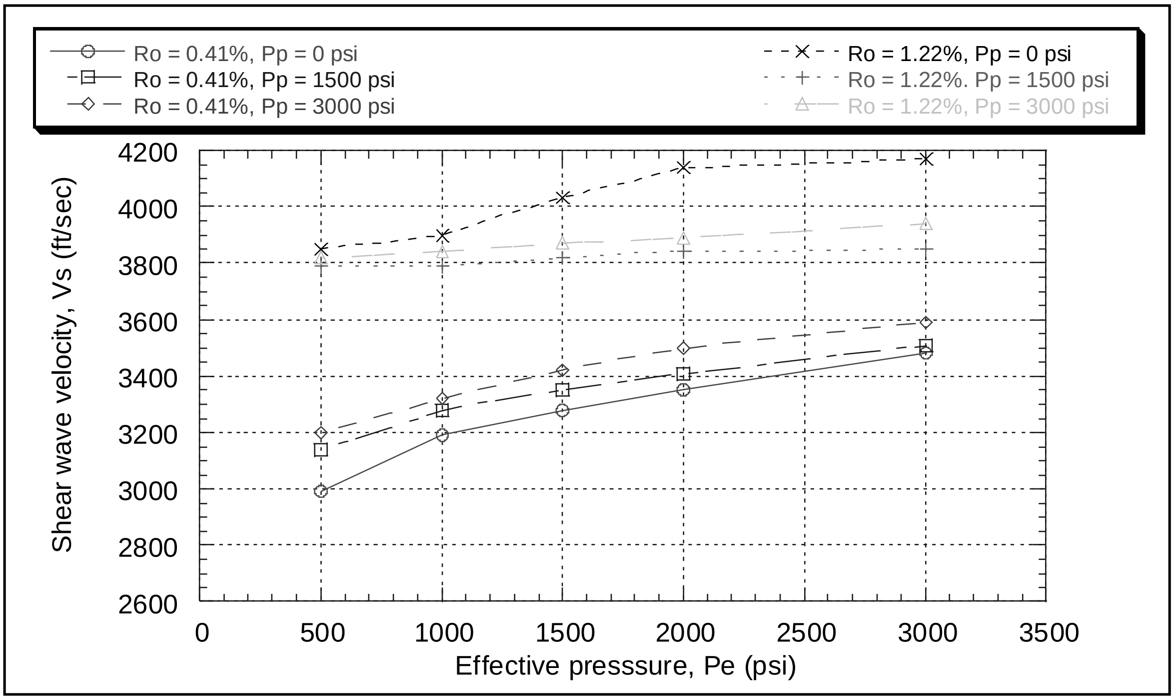

FIGURE 11. Dry coal samples under methane pore pressure. Shear wave velocity versus effective pressure of el Roble coal sample, (Ro = 1.22%), and Fort union coal sample, (Ro = 0.41%). The plot illustrates difference in Vs in perpendicular plugs from dry coal samples. Conversion factors: 1ft/sec = 0.305 m/sec; 1 psi = 6.885 KPa.

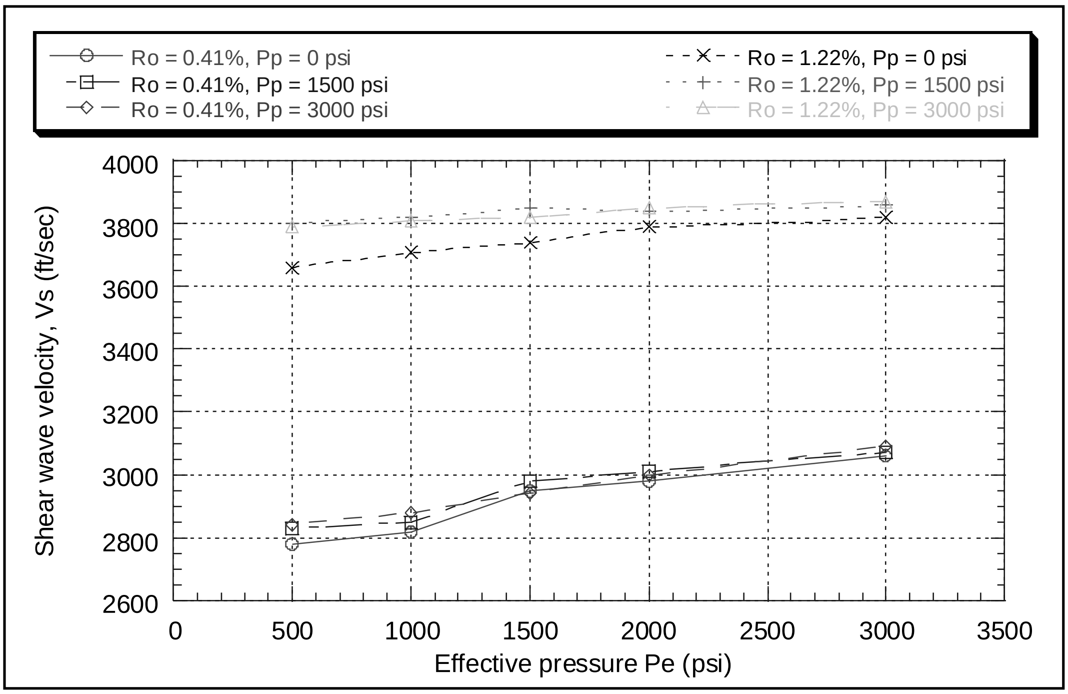

FIGURE 12. Water-saturated coal samples under methane pore pressure. Shear wave velocity versus effective pressure plot. El Roble coal sample, (Ro = 1.22%), and Fort Union coal sample, (Ro = 0.41%). Notice the differences in Vs in perpendicular plugs from these two coal samples. Conversion factors: 1ft/sec = 0.305 m/sec; 1 psi = 6.885 KPa.

Simulation of coalbed reservoir conditions in laboratory experiments.

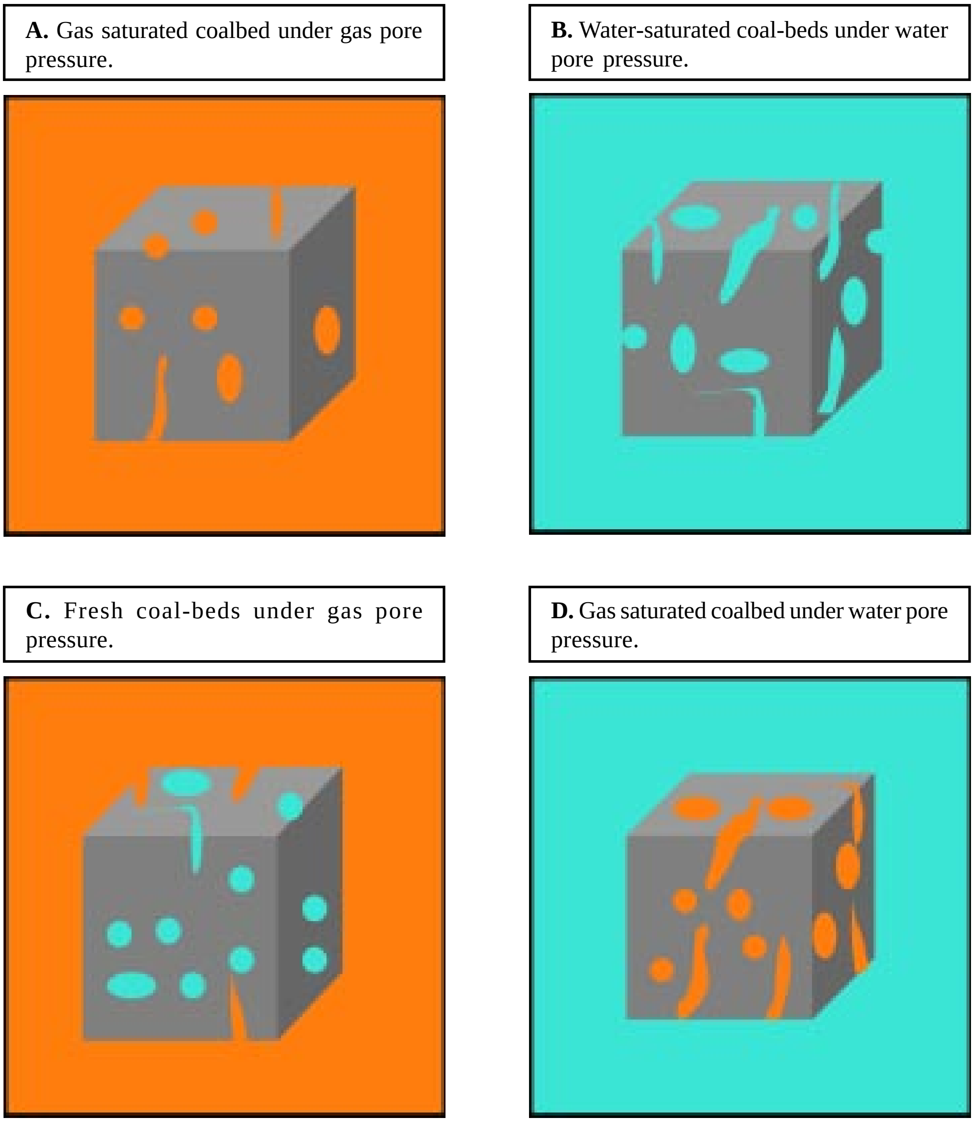

FIGURE 13. Schematic representation of four different situations of coalbed methane reservoirs. The figure illustrates a cube of porous coal under gas pore pressure (in orange) or water pore pressure (in blue). Pores and fractures are filled either with gas (orange) or water (blue).

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