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SEALING PROPERTIES OF BENTONITE SUSPENSIONS*

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Abstract – Sealing with waterborne clays is a rapid and low cost method of controlling seepage through porous media whenever the clay source is within economical shipping distance of the sealing site. But more must be learned about this method of sealing before it can be fully utilized.

Water impedance of waterborne bentonites, as measured by water loss in the filter press test, was correlated with their physical, chemical and mineralogical properties. A multiple linear regression analysis showed clay content and exchangeable sodium percentage (ESP) were most highly correlated with water impedance. Swelling, viscosity and gelation of these clays play only a secondary role in forming a water barrier when used as dilute waterborne sealants as suggested by these and other data.

There were strong positive correlations between water loss and samples high in silt-sized cristobalite, quartz and feldspar; and negative correlations between water loss and samples high in clay-sized montmorillonite, chlorite and illite.

Predicted minimum clay contents (of prospective sealers) were found to be 65–75 per cent clay at 70 and 20 per cent exchangeable sodium, respectively.

INTRODUCTION

WATERBORNE clay is a rapid and low cost method of sealing porous media whenever the clay source is within economical shipping distance of the sealing site. Since high-swelling bentonites commonly exist in the Western United States (Gunsallus and Waters, 1957), these clays could be used more extensively in this region in reducing seepage losses from water storage or conveyance structures. But more must be learned about this method of sealing before it can be fully utilized.

A number of studies listed in the references have been concerned with factors influencing clay penetration and retention in porous media. None of these studies, however, investigated those properties of the clays that directly influence water impedance. It was the purpose of this study to determine the physical, chemical and mineralogical properties of bentonites that most closely correlate with their water impedance. A knowledge of these properties should then permit simple laboratory analysis to determine a good clay sealant. Once the properties of clays that reduce water loss are clearly defined, then other factors that influence and control penetration and retention of clays in porous media can be further studied and more effectively utilized.

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A filter press apparatus was used to measure the water impedance of waterborne bentonites in this study. It has been found that seals formed in porous media are similar to seals formed in a filter press apparatus. Curry and Beasley (1960) showed that mechanical filtering is the main process by which clay particles are removed from suspension when flowing through porous media. Rollins (1967) has recently found evidence that a tight seal is formed by bentonite accumulating near the surface of the sand when sealing with waterborne bentonite. Therefore, since surface seals are formed when sealing porous media with waterborne clays, as well as in the filter press, the filter press test should be a representative water impedance measurement of waterborne clays.

PROCEDURE

Water loss

Water loss from duplicate 6 per cent bentonite suspensions was measured with a standard Baroid† filter press using a pressure of 14·7 psi for 30 min. This was a modification of the standard technique (A.P.I., 1957) in that the pressure was lowered from 100 to 14·7 psi. The test cell measured 3 in. I.D. and 3·5 in. long, and was filled to a volume of 380 ml ($\frac{1}{4}$-in. from top). A standard 9-cm filter paper (Baroid No. 987) was used in the test.

†The use of this equipment does not imply approval of the product to the exclusion of others that may be suitable.

The filter press test measures the ability of a clay suspension to form a low permeability filter cake on a standard filter paper. The lower the permeability, the lower the volume of filtrate (water loss) from the suspension. It should be remembered that this test measures the amount of water lost during seal development. More time and bentonite are required to form tight seals in sands. It would require several days and the entire bentonite suspension contained in each cell of the filter press to seal an equivalent surface area of sand.

This study included eighteen bentonites from major deposits in the Western United States. All deposits are large enough to be of economic importance, and most are producing bentonite commercially.

Physical measurements

Physical properties measured were particle size, swelling, viscosity and gelation. Particle size was determined by Fisk's method (1946), slightly modified. This involved dispersing triplicate 10-g samples in 500 ml of distilled water in a blendor for 4 min at low speed. Each suspension was then transferred to a graduated cylinder and diluted with more water until the 12-in. depth was reached (1000 ml). Particles remaining in suspension after 24 hr were then carefully decanted and calculated as particles less than 2 μ. The residue in the bottom of the cylinder was dried and weighed. Sand greater than 43 μ was measured by the amount retained on a 325-mesh sieve. The remaining residue was assumed to be silt of 2–43 μ size.

The volume of swell was measured according to a procedure of the American Colloid Co. (1945). This involved dropping duplicate 2 g samples of bentonite (small portions at a time) into 100 ml of distilled water. The volume of "free swell" was measured 1 hr later.

The viscosity and gel strength were measured with a Baroid viscometer, model 35, Fann V-G meter according to its operating instructions. This is a direct reading instrument. Duplicate samples of each bentonite were prepared for viscosity and gel measurements by dispersing in distilled water as a $6\frac{1}{4}$ per cent suspension according to the American Colloid Co.

Chemical measurements

Samples were air dried and passed through a 60-mesh sieve. For the determination of soluble salts, triplicate 20-g samples were dispersed in 250 ml of distilled water by shaking for 10 min in 500-ml Erlenmeyer flasks. One minute of shaking was done by hand, followed by 9 min on a gyrosolver mechanical shaker. The samples were allowed to stand for 24 hr before removing the water extract with a Baroid filter press apparatus, using a Baroid No. 987 filter paper and a pressure of 100 psi. Whenever possible, analyses were done within 24 hr after extraction.

Exchangeable cations and cation exchange capacities were measured as described by Rollins and Pool (1968). Triplicate samples of 0·5 g were used in each analysis. Exchangeable cations were removed by three extractions of 25-ml volumes of ammonium acetate. CEC was measured using Na as the index cation (saturated with four 25-ml volumes of sodium acetate) followed by extraction with three 25-ml volumes of ammonium acetate.

Calcium plus magnesium was determined by titration with versenate using Eriochrome Black T as an indicator (U.S. Salinity Lab., 1954). Potassium and sodium were analyzed with a Beckman model DU flame photometer.

Mineralogical

The Carter *et al.* (1965) method was used to determine surface area. The percentage of montmorillonite in the clay and silt fractions was estimated from surface area measurements as suggested by McNeal (1964), and the contents of additional minerals were estimated by X-ray diffraction.

RESULTS

Water loss

The results of the water loss measurements are presented in Table 1. All five of the bentonites that flocculated as 6 per cent suspensions lost more than 24 ml of water. Flocculation, however, was not the entire cause of high water loss in these samples. The low clay content of most of these flocculating samples also contributed to their high water loss. This was verified with a regression equation developed from the data (see topic on critical levels of ESP and per cent clay). The mean loss of 20·6 ml was chosen as a dividing line between good and poor sealers. All samples that did not flocculate lost less than 20 ml of water during the 30-min test.

Physical properties

Only two bentonite samples contained less than 50 per cent clay (Table 1); but the range in clay content was wide, varying from 32·5 to 82·8 per cent. It will be shown below that a clay content of 65 per cent or greater is necessary for a good sealing bentonite.

Flocculating bentonites also exhibited the lowest volume of swell after 1 hr of wetting. Sample

Table 1. Physical properties of eighteen bentonites from the Western United States

No.*	Clay < 2 μ (%)	Silt 2–43 μ (%)	Grit > 43 μ (%)	Water loss† (ml)	Volume of swell (ml)	Plastic viscosity (cps)	Gel strength @ 5 min. (lbs/100 sq. ft.)
2	80·7	15·8	3·5	12·1	46	27	60
4	76·1	15·4	8·5	14·0	35	9	47
5	82·8	15·7	1·5	24·8‡	15	3	9
6	62·1	32·3	5·6	19·5	21	6	7
8	81·4	14·6	4·0	14·7	35	9	55
9	64·2	34·8	1·0	12·5	6	1·5	0
10	69·1	26·0	4·9	17·5	20	3	13
11	51·6	37·7	10·7	27·5‡	10	3	7
12	47·5	43·8	8·7	49·1‡	7	2·5	1·5
13	82·0	15·3	2·7	15·4	35	11	58
14	51·9	29·8	18·3	16·7	17	4	3·5
15	75·5	19·4	5·1	9·1	15	5	1
16	61·8	26·4	11·8	15·7	20	4	5
18	81·4	15·2	3·4	12·6	41	11	100
19	32·5	56·3	11·2	58·1‡	5·5	1·5	0·5
21	80·5	15·7	3·8	10·7	29	21	5
23	56·2	32·2	11·6	28·0‡	4	1·5	0·5
25	76·0	13·0	11·0	13·2	16·8	4	1
Means							
$\bar{x}$	67·4	25·5	7·1	20·6	21·0	7·1	20·8
Range	32·5 to 82·8	13 to 56·3	1·0 to 18	9·1 to 58·1	4·0 to 46	1·5 to 27	0 to 100

*For location of bentonite samples refer to Table 2.
†Volume of water lost during 30 min from a filter press under a pressure of 14·7 psi.
‡These bentonites flocculated as 6 per cent suspensions.

no. 9 was the only low-swelling clay that did not flocculate.

Viscosity and gel strength measurements are also shown in Table 1. By way of comparison, water has a viscosity of 1·005 cP at 20°C. A 6¼ per cent suspension of several of these bentonites was hardly more viscous than water, but viscosity values were poorly related to water loss. Measurements of gel strength taken after the bentonite suspensions had stood undisturbed for 5 min varied widely, and were also poorly related to filter press water loss. Thus neither of these techniques appears very promising as a routine laboratory method for appraising sealing potential of bentonites.

Chemical properties

Chemical properties of the bentonites are presented in Table 2. Exchangeable cations were calculated by subtracting water-soluble cations from ammonium acetate-extractable cations. The bentonites contained high amounts of exchangeable Na, moderate amounts of exchangeable Ca and Mg, and low amounts of exchangeable K. Only two bentonites (nos. 5 and 23) contained less than 30 per cent exchangeable Na (ES) and these were flocculating bentonites. Sufficient ES to disperse the clay particles appears to be essential for a good sealing bentonite.

Chemical properties of the bentonites varied with geographical area, from deposit to deposit within a geographic area, and even within a given deposit. This latter variation is shown by the deposit in western Nevada (samples 11 and 12). Williams *et al.* (1954) have reported a substantial change in bentonite chemical properties with change in depth of overburden.

Total exchangeable cations and CEC agreed well in most cases, demonstrating the reliability of the measurements.

Mineralogy

Table 3 shows the mineralogical analysis of the bentonites used in the study. Montmorillonite contents were calculated from ethylene glycol monoethylether retention (Carter *et al.*, 1965).

Table 2. Chemical properties of eighteen bentonites from the Western United States

No.	Bentonite sample Location	Exchangeable Ca + Mg (meq/100 g)	Exchangeable Na (meq/100 g)	Exchangeable K (meq/100 g)	Total exchangeable cations (meq/100 g)	Exchangeable Na percentage	C.E.C. meq/100 g	Total sol. salts meq/100 g‡
2	Greybull, Wyo.	24·6	45·9	1·22	71·7	64·0	72·6	16·1
4	Colony, Wyo.	48·1*	40·4	1·71	90·2	44·7	90·2	18·5
5	Nampa, Ida.	65·1	11·2	0·50	76·8	14·6†	78·5	116·5
6	Casper, Wyo.	13·9*	62·7	1·46	78·1	80·3	78·1	27·7
8	Belle Fourche, S. Dak.	61·8	31·2	1·27	93·3	33·4	90·4	35·1
9	Death Valley, Calif.	10·6*	28·6	3·54	42·8	66·9	42·8	8·6
10	Nixon, Nev.	10·8*	72·8	3·79	87·4	83·3	87·4	41·6
11	Thorn, Nev.	24·7	34·7	1·05	60·5	57·4†	56·0	30·7
12	Thorn, Nev.	27·5	27·2	0·88	55·5	48·9†	53·6	87·2
13	Belle Fourche, S. Dak.	49·5*	34·2	1·57	85·2	39·1	85·2	23·5
14	Ivie-Aurora, Utah	14·2*	44·4	1·54	60·2	73·8	60·2	29·1
15	Cannonville, Utah	7·6*	65·7	2·40	75·7	86·8	75·7	6·7
16	Baker, Nev.	29·4*	30·7	1·50	61·6	49·8	61·6	16·1
18	Moorcroft, Wyo.	22·2*	58·9	1·76	82·9	71·1	82·9	24·7
19	Salida, Colo.	53·4*	27·5	2·63	83·6	32·9†	83·6	2·1
21	Greybull, Wyo.	25·0	39·7	0·05	64·7	61·3	72·5	15·2
23	Lovelock, Nev.	28·6	9·3	0·69	38·6	12·2†	75·8	2·5
25	Silver Peak Nev.	22·7	25·6	2·00	50·3	39·0	65·6	12·0
	Means $\bar{x}$	30·0	38·4	1·64	70·0	53·3	72·9	28·6

*These bentonites contained additional calcium and magnesium salts not soluble in water. These were most likely carbonates and sulfates which were solubilized by the ammonium acetate extraction.

†Flocculating bentonite.

‡Total salts were measured with a salt bridge, from an extract of 1 part bentonite to 12·5 parts distilled water.

The retention value used for pure montmorillonite was 800 m²/g, (slightly less than the Dyal and Hendricks (1950) value of 810 m²/g). Many of the clays were lower in montmorillonite than expected.

By definition, bentonites are montmorillonites of volcanic origin (Hewett, 1917. Ross and Shannon, 1926). Two samples contained less than 30 per cent montmorillonite in the clay fraction and may not have been bentonites in the strictest sense (i.e., samples 9 and 19) even though montmorillonite was the predominant clay mineral in each sample. All clays in the study, however, had chemical properties characteristic of high swelling bentonites in that they were high in exchangeable Na and low in exchangeable K (Ross and Hendricks, 1945).

The montmorillonite contents are probably accurate to within ± 5 per cent, but other minerals may be in error by as much as 10–15 per cent. Amorphous material was not measured, and if present in appreciable amounts, would lower the nonmontmorillonite values more or less in a 1 : 1 ratio. According to Ross and Shannon (1926), the amorphous material in most commercial bentonites is generally low, but it could be higher in some of the less characteristic materials.

STATISTICAL ANALYSIS

Properties correlated with water loss

Water impedance of the clays, as measured by water loss in the filter press test, were correlated with their physical, chemical and mineralogical properties. A multiple linear regression analysis was performed on all variables studied, using water loss as the dependent variable.

Clay content and ESP were most highly correlated with water impedance (or negatively correlated with water loss) (Table 4). Clay content shows the strongest correlation with water impedance, as evidenced by its highly significant simple and partial correlation coefficients and

Table 3. Mineralogical composition of eighteen bentonites form the Western United States

Sample No.	Location	Size fraction	Mont. %*	Other minerals* (%)											
2	Greybull,	clay	56	cristob.	16	chlor.	8	illite	0	feld.	0				
	Wyoming	silt	2		2		0		6		6				
4	Colony,	clay	57	feld.	19	illite	0	quartz	0						
	Wyoming	silt	2		3		5		5						
5	Nampa,	clay	46	cristob.	37	quartz	0								
	Idaho	silt	4		8		4								
6	Casper,	clay	50	quartz	9	cris.	3	calcite	0	feld.	0	illite	0		
	Wyoming	silt	3		19		2		3		3		2		
8	B. Fourche,	clay	57	quartz	16	cris.	8	feld.	0	illite	0				
	S. Dak.	silt	2		7		0		4		2				
9	Death Valley,	clay	29	calcite	17	illite	18	chlor.	0	talc	0	quartz	0	feld.	0
	Calif.	silt	0		19		2		5		5		2		2
10	Nixon,	clay	55	feld.	0	chlor.	14	cris.	0						
	Nevada	silt	1		22		0		3						
11	Thorn,	clay	39	cris.	13	feld.	0	quartz	0						
	Nevada	silt	6		19		9		4						
12	Thorn,	clay	31	feld.	0	cris.	10	chlor.	7	illite	0				
	Nevada	silt	4		26		9		0		4				
13	B. Fourche,	clay	74	feld.	8	cris.	0	illite	0						
	S. Dak.	silt	3		3		6		3						
14	Ivie-Aurora,	clay	36	cris.	16	calcite	0	feld.	0	quartz	0				
	Utah	silt	2		7		10		8		3				
15	Cannonville,	clay	60	quartz	15	illite	0	feld.	0	kaol.	0				
	Utah	silt	3		11		4		1		1				
16	Baker,	clay	40		22		0		0		0		0		
	Nevada	silt	1	cris.	3	dolomite	15	quartz	3	feld.	3	illite	1		
18	Moorcroft,	clay	69	quartz	12	feld.	0	illite	0	kaol.	0				
	Wyoming	silt	2		9		3		1		1				
19	Salida,	clay	29	cris.	4										
	Colo.	silt	28		28										
21	Greybull,	clay	72	cris.	4	feld.	0	biotite	0	chlor.	4				
	Wyoming	silt	2		5		5		4		0				
23	Lovelock,	clay	45	cris.	11										
	Nevada	silt	13		19										
25	Silver Peak,	clay	57	cris.	19	feld.	0	illite	0						
	Nevada	silt	2		4		6		1						

*Mineral content was calculated on whole sample basis and does not include minerals of sand-sized particles.

regression coefficient. F values are highly significant for each set of data that includes clay content (including additional sets of data not shown here). The simple correlation for ESP is rather weak but the partial correlation is strong, indicating a masking effect (statistically) (Kendall and Stuart, 1961) upon the ESP by one or more of the other variables.

Swelling shows a strong simple correlation, but the partial correlation coefficient was nearly zero, inferring that the relationship between this property and water loss is attributed to an interdependence of clay content or ESP. Pairing swelling with each of these properties as well as total salts showed this interdependence was attributed to clay content. Neither ESP nor total salts showed any interdependence with swelling.

Viscosity and gelation showed the same interdependence with clay content as did swelling. These two properties also showed no interdependence with ESP or total salts. These and other data suggest that swelling, viscosity and gelation of these clays play secondary (but often important) roles in forming a water barrier when used as dilute waterborne sealants. For example, shrinking and swelling of the bentonites with drying and wetting of the soil surface (Rollins and Dylla, 1964), additional swelling with time, once particles are in place (Rollins *et al.*, 1961), and failure of highly viscous and gel-like suspensions to penetrate coarse sands (Rollins, 1967) can all make these three properties important in choosing clays for sealing purposes under particular circumstances. Thus measurement of these properties should

Table 4. Relationships between physical and chemical properties and water loss from eighteen bentonites (water loss is dependent variable)

Variable	Mean	Stand. deviat.	F value	Coefficients Multiple corr.	Simple corr.	Partial corr.	Regression equation
			$22{\cdot}3_{0{\cdot}005}$†	0·865			
X_1 % clay	67·4	14·8			$-0{\cdot}787_{0{\cdot}01}$	$-0{\cdot}838_{0{\cdot}001}$	$Y = 78{\cdot}6 - 0{\cdot}691X_1 -$
X_2 ESP	53·3	22·2			$-0{\cdot}394_{0{\cdot}10}$	$-0{\cdot}582_{0{\cdot}025}$	$0{\cdot}214X_2$
Y Water loss	20·6	13·2*					
			$14{\cdot}4_{0{\cdot}005}$	0·869			
X_1 % clay	67·4	14·8			$-0{\cdot}787_{0{\cdot}01}$	$-0{\cdot}764_{0{\cdot}001}$	$Y = 81{\cdot}9 - 0{\cdot}771X_1 -$
X_2 ESP	53·3	22·2			$-0{\cdot}394_{0{\cdot}10}$	$-0{\cdot}597_{0{\cdot}025}$	$0{\cdot}226X_2 + 0{\cdot}126X_3$
X_3 Swelling	21·0	13·0			$-0{\cdot}569_{0{\cdot}02}$	0·165	
			$12{\cdot}2_{0{\cdot}005}$	0·787			
X_1 % clay	67·4	14·8			$-0{\cdot}787_{0{\cdot}01}$	$-0{\cdot}661_{0{\cdot}005}$	$Y = 68{\cdot}2 - 0{\cdot}707X_1 +$
X_3 Swelling	21·0	13·0			$-0{\cdot}569_{0{\cdot}02}$	0·003	$0{\cdot}003X_3$
			$5{\cdot}23_{0{\cdot}025}$	0·641			
X_2 ESP	53·3	22·2			$-0{\cdot}394_{0{\cdot}10}$	$-0{\cdot}358_{0{\cdot}20}$	$Y = 41{\cdot}2 - 0{\cdot}178X_2 -$
X_3 Swelling	21·0	13·0			$-0{\cdot}569_{0{\cdot}02}$	$-0{\cdot}550_{0{\cdot}025}$	$0{\cdot}526X_3$
			$4{\cdot}38_{0{\cdot}025}$	0·607			
X_3 Swelling	21·0	13·0			$-0{\cdot}569_{0{\cdot}02}$	$-0{\cdot}566_{0{\cdot}025}$	$Y = 29{\cdot}7 - 0{\cdot}560X_3 +$
X_4 Total salts	28·6	29·3			0·265	$0{\cdot}256_{0{\cdot}30}$	$0{\cdot}096X_4$
			$12{\cdot}2_{0{\cdot}005}$	0·787			
X_1 % clay	67·4	14·8			$-0{\cdot}787_{0{\cdot}01}$	$-0{\cdot}730_{0{\cdot}001}$	$Y = 68{\cdot}6 - 0{\cdot}717X_1 +$
X_5 Viscosity	7·06	6·97			$-0{\cdot}431_{0{\cdot}10}$	0·029	$0{\cdot}041X_5$
			$13{\cdot}1_{0{\cdot}005}$	0·797			
X_1 % clay	67·4	14·8			$-0{\cdot}787_{0{\cdot}01}$	$-0{\cdot}766_{0{\cdot}001}$	$Y = 72{\cdot}0 - 0{\cdot}783X_1 +$
X_6 Gelation	20·8	29·5			$-0{\cdot}339$	0·204	$0{\cdot}068X_6$
			$24{\cdot}1_{0{\cdot}005}$†	0·939			
X_7 % silt	25·5	12·2			$0{\cdot}826_{0{\cdot}01}$	$0{\cdot}911_{0{\cdot}001}$	$Y = -14{\cdot}4 + 0{\cdot}917X_7$
X_8 Exch. Ca + Mg	30·1	18·1			0·309	$0{\cdot}691_{0{\cdot}005}$	$+ 0{\cdot}260X_8 + 0{\cdot}085X_4$
X_4 Total salts	28·6	29·3			0·265	$0{\cdot}446_{0{\cdot}10}$	$+ 0{\cdot}202X_9$
X_9 % sand	7·07	4·62			0·331	0·178	

*Water loss is the dependent variable in each set of data, although it is only shown in the first set of data.
†Subscript numerals indicate levels of significance.

probably be included in any complete characterization of prospective sealers.

Properties positively correlated with water loss were silt content, exchangeable Ca plus Mg, and total salts as shown in Table 4. The F value and multiple correlation coefficients are very high for this set of data, indicating that changes in these properties are related to changes in water loss. Sand content was shown to be an insignificant factor, probably due to its low content in these samples. The influence of total salts upon water loss was rather weak as shown by the low partial correlation and regression coefficients. There were no strong interactions between properties positively correlated with water loss as there were between properties negatively correlated with water loss.

Correlation of mineralogical composition with water loss

Sergueev (1954) suggested that mineralogical composition, as well as chemical and physical composition, determine the ability of clay particles to penetrate a sand. He substantiates his reasoning with the observation that minerals with a sliding crystal structure yield a clay higher in colloids than minerals with a rigid crystal structure. The following statistical analysis of the data collected in this study generally substantiates Sergueev's claims.

Because particle size was highly correlated with water loss, mineral composition of each clay and silt sized fraction was related to water loss by multiple regression analysis (Table 5). The results demonstrated a positive correlation between water

Table 5. Relationships between water loss and amounts of major minerals found in eighteen bentonites (water loss is dependent variable)

Variable	Mean	Stand. deviat.	F value	Multiple corr.	Simple corr.	Partial corr.	Regression equation
	silt size (%)		$1{\cdot}85_{0{\cdot}25}$†	0·602			
X_{10} Cristob.	6·83	7·99			0·331	$0{\cdot}509_{0{\cdot}05}$	$Y = 12{\cdot}5 + 0{\cdot}236X_{10} +$
X_{11} Quartz	3·67	4·59			0·146	$0{\cdot}408_{0{\cdot}10}$	$0{\cdot}224X_{11} + 0{\cdot}102X_{12}$
X_{12} Feldspar	5·56	7·07			0·257	0·302	$-0{\cdot}141X_{13}$
X_{13} Mont. plus illite	6·44	6·26			0·027	−0·266	
Y Water loss – ml	14·6*	2·58					
	clay size (%)		$1{\cdot}58_{0{\cdot}25}$	0·417			
X_{14} Mont., chlor. & illite	52·9	13·9			$-0{\cdot}416_{0{\cdot}10}$	$-0{\cdot}414_{0{\cdot}10}$	$Y = 18{\cdot}9 - 0{\cdot}078X_{14} -$
X_{15} Non-clay minerals	13·6	8·28			0·052	−0·036	$0{\cdot}011X_{15}$
Y Water loss – ml	14·6*	2·58					

*Mean water loss of all samples after excess salts were washed from flocculating samples.
†Subscript numerals indicate levels of significance.

loss and content of silt-sized nonclay minerals (e.g., cristobalite, quartz and feldspar), and a negative correlation between water loss and amounts of clay-sized minerals (e.g., montmorillonite, chlorite and illite). Amounts of silt-sized clay minerals and clay-sized nonclay minerals showed insignificant correlations with water loss.

Critical levels of ESP and per cent clay

Since clay content and ESP were the properties most highly correlated with water impedance, the data were used to establish critical levels from these two properties. Predicted levels of clay content at certain ESP levels were calculated from the regression equation: $\%\text{clay} = A + K_1 \times (\text{ESP}) + K_2 \times (\text{water loss})$. A permissible level for water loss was taken as 20 ml per 30 min of testing (see discussion under water loss). Figure 1 presents the predicted clay contents calculated for various ESP levels at three different water loss levels. At an ESP level of 50, the predicted clay content necessary to hold the water loss at 20 ml is 70 per cent. If the ESP drops to 20 per cent, which is still ample sodium to disperse most clays, the predicted clay content needed to form a good seal increases to 75 per cent. It becomes further apparent that clay content is the most critical component of waterborne sealers.

The regression equation used to develop Fig. 1, verifies that four of the five flocculating bentonites in this study would be poor waterborne sealers because they lack sufficient clay-sized particles to impede water movement. The exception, sample

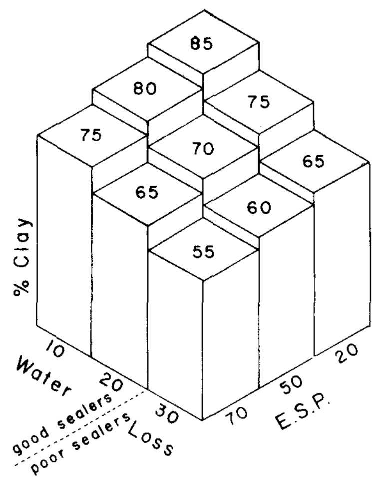

Fig. 1. Predicted clay content necessary to hold water loss at various levels with exchangeable sodium percentage at certain levels. Per cent clay was calculated by using the following regression equation: $Y = 99{\cdot}48 - 0{\cdot}209X_1 - 1{\cdot}02X_2$, $Y = \%$ clay, $X_1 =$ ESP, $X_2 =$ water loss. Standard error of estimate = 8·6.

no. 5, would probably become a good sealer when the high total soluble salts were leached out after seal installation.

CONCLUSIONS

The results of this study suggest that bentonites to be used as waterborne sealants have two simple, but prime requirements: (1) a high clay content, and (2) sufficient ES content to form a dispersed structure. Predicted minimum clay contents at

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various ESP levels that would normally produce a good seal were found to be 65–75 per cent clay at 70 and 20 per cent ES, respectively. Other physical, chemical and mineral properties appear to be less significant.

Total salt content of the clays did not correlate strongly with water loss, probably because the salts were well diluted during the filter press tests. In practice, salts in the water at the sealing site would eventually reach an equilibrium composition with the clay sealer and would, therefore, be much more important than salts contained in the bentonites in determining water impedance of the seals.

Mineralogical analysis showed that poor sealers were high in minerals with a rigid crystal structure such as cristobalite, quartz and feldspar. Those clays that contained the highest total montmorillonite, chlorite and illite of clay-sized particles were the best sealers.

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Résumé—L'obturation au moyen de suspensions d'argile dans de l'eau est un moyen rapide et économique de contrôler les infiltrations à travers les média poreux toutes les fois que la source d'argile se trouve à une distance d'expédition économique de l'emplacement où l'obturation est nécessaire. Pourtant il faut obtenir plus de renseignements concernant cette méthode d'obturation avant de pouvoir l'employer de manière optimum.

L'impédance à l'eau des suspensions aqueuses de bentonite, mesurée sur la base de la perte d'eau dans l'essai à la presse de filtrage a été corrélée avec leurs propriétés physiques, chimiques et minéralogiques. Une analyse multiple de régression linéaire a montré que la teneur en argile et le pourcentage de sodium échangeable (ESP) avaient la corrélation la plus importante avec l'impédance à l'eau. Le gonflement, la viscosité et la gelation de ces argiles jouent seulement un rôle secondaire dans la formation d'une barrière d'eau dans le cas d'emploi en tant qu'agents d'obturation en suspension aqueuse selon les données présentées ici et ailleurs.

Il y avait une corrélation positive et importante entre la perte d'eau et les échantillons à haute teneur en cristobalite vaseux, quartz et feldspar. Des corrélation négatives existaient entre la perte d'eau et les échantillons à teneur élevée en montmorillonite, chlorite et illite argileux.

La teneur minimum anticipée en argile pour les agents d'obturation était entre 65 et 75 pour cent d'argile avec 70 et 20 pour cent sodium échangeable.

Kurzreferat—Die Abdichtung mit Hilfe Ton-Suspensionen ist eine schnelle und billige Methode, um das Sickern durch poröse Media einzuschränken, vorausgesetzt, dass sich die Quelle der Tonminerale vom Standpunkt des Transportes wirtschaftlicher Entfernung von dem Ort der gewünschten Abdichtung befindet. Ehe diese Methode der Abdichtung zur vollen Anwendung kommt, muss sie jedoch zunächst noch in mancher Hinsicht erforscht werden.

Die Wasserimpedanz Wässeriger Bentonit-Suspensionen, gemessen an dem Wasserverlust im Filterpressversuch, wurde in eine Beziehung zu den physikalischen, chemischen und mineralogischen Eigenschaften der Bentoniten gebracht. Eine mehrfache lineare Regressionsanalyse zeigte, dass der Tongehalt und der Gehalt an austauschbarem Natrium (ESP) in engster Korrelation zur Wasserimpedanz standen. Wie diese und andere Daten zeigte, spielten bei Verwendung dieser Stoffe als verdünnte wässerige Abdichtungsmittel das Quellvermögen, die Zähigkeit und die Gelierung dieser Tone nur eine zweitrangige Rolle in der Bildung einer Wasserschranke.

Stark positive Korrelationen bestanden zwischen dem Wasserverlust und Proben mit hohem Gehalt an Cristobalit, Quarz und Feldspat in Schluffgrösse, während negative Korrelationen zwischen Wässerverlusten und Proben mit hohem Gehalt an Montmorillonit, Chlorit und Illit in Tongrösse festgestellt wurden.

Die minimalen Tongehalte (voraussichtlicher Abdichter) betrugen 65 bis 75 Prozent Ton bei einem entsprechenden austauschbaren Natriumgehalt von 70 bzw. 20 Prozent.

Резюме—Изоляция при помощи переносимых водой глин—это быстрый и дешевый метод регулирования просачивания через пористые породы во всех тех случаях, когда источник глины находится на зкономически оправдывающемся расстоянии от изолируемого участка. Однако, прежде чем можно будет полностью использовать этот метод изоляции, придется узнать больше о нем.

Водяной импеданс переносимых водой бентонитов, измеряемый потерей воды в фильтрпрессном испытании, был сопоставлен с их физическими, химическими и минералогическими свойствами. Анализ многократного линейного возвращения показал, что глиносодержание и процент обменного натрия были особо тесно связаны с импедансом воды. Набухание, вязкость и жеетинизация этих глин играют лишь второстепенную роль в образовании водяного барьера, пользуясь ими в качестве разбавленных переносимых водой укупоривающих средств, как это подсказывается этими и другими данными.

Имеются сильные положительные корреляции между потерей воды и образцами, содержащими крупное количество кристобалита, кварца и полевого шпата в размере пылеватой фракции; а отрицательные корреляции существуют между потерей воды и образцами, содержащими много монтмориллонита, хлорита и иллита в размере глинистых фракций.

Предсказываемое минимальное глиносодержание возможных уплотнителей составляет 65 до 75% глины при 70 и 20% обменного натрия соответственно.