INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

Residual Strengths of Mineral Mixtures

Résistances Résiduelles de Divers Mélanges de Minéraux

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SYNOPSIS: Residual strength properties are reported for mineral mixtures composed of a massive mineral (quartz) and a clay mineral (montmorillonite, hydrous mica or kaolinite). The clay minerals were prepared in homoionic states with several different cations at several different salt concentrations in the pore fluids. The results indicate that residual strength is dependent on mineral composition of the mixture and chemical state of the clay mineral. Residual strength properties of several natural soils in untreated and chemically-treated conditions are compared to those of mineral mixtures. The results are consistent for soils and mineral mixtures in which the dominant clay mineral is montmorillonite. In the case of soils and mineral mixtures in which the dominant clay mineral is hydrous mica unexplained anomalies exist among the residual-strength results.

INTRODUCTION

As a contribution to the Geotechnical Conference Oslo 1967 on shear strength properties of natural soils and rocks the author presented the results of residual-strength tests on minerals, natural soils and a small number of mixtures of clay minerals and massive minerals. For mineral mixtures and natural soils in which montmorillonite was the dominant clay mineral the two sets of test results compared very well, whereas in the case of mineral mixtures and natural soils in which hydrous mica was the dominant clay mineral the residual strengths of the natural soils were considerably larger than those of the mineral mixtures.

This paper presents the results of additional tests and, in particular, the results of an investigation of the inconsistencies between residual strengths of natural soils and mineral mixtures containing hydrous mica.

Methods used in the test program for preparing homoionic clay minerals and soils, for determining quantitatively the mineral compositions of soils and for performing direct-shear tests to determine residual strength are the same as those described in detail by Kenney (1967).

MATERIALS USED IN MIXTURES

Characteristics and properties of materials used in the mixtures are listed in Table I. Crushed quartz was used as the massive-mineral component for most of the mineral mixtures, but in a few cases amorphous SiO_2 (in the form of very small spheres) was used instead of quartz.

Montmorillonite (Table Ia) was chosen to represent highly-active and expansive clay minerals and it was obtained by removing all particles greater in size than 2 microns from a bentonite commercially identified as KWK.

Hydrous mica (10 Å reflection in X-ray diffraction analysis) was chosen to represent inactive clay minerals of the mica group. It was obtained by removing particles greater than 2 microns from a post-glacial marine quick clay from Selnes, Norway and, as reported in Table 1b, it was not pure but contained other minerals, particularly massive minerals. This was not considered to be a serious shortcoming because the hydrous mica was to be used in mixtures with quartz. Three different batches were prepared: hydrous mica I and hydrous mica II are the <2 micron fraction of two different samples from Selnes and hydrous mica III is the <0.5 micron fraction of hydrous mica II.

The third clay mineral used in the investigation was kaolinite (Table Ic) which was virtually pure. This mineral was more coarse-grained than the others (<10 microns).

Two other materials were used to make mixtures. A commercial bentonite (Table 1a) was used without chemical treatment. The second material is known commercially as grundite (Table Ic), and contains a large amount of hydrous mica (or illite) but also contains an important amount of mixed-layer clay minerals which have characteristics somewhere between those of hydrous mica and montmorillonite.

TEST PROCEDURES

Mineral mixtures were made by mixing thoroughly known amounts of dry quartz or SiO_2 with specimens of wet clay having known contents of dry minerals. The characteristics of the mixtures are listed in Table II.

The material to be tested was prepared to a water content exceeding the liquid limit and placed within a confining ring as a 2 mm thick layer between two carborundum plates 8 cm diameter (area=50 cm^2) and consolidated in direct-shear machines of the type described by Bjerrum and Landva (1966). After consolidation the confining ring was removed and the sample was sheared backwards and forwards over a distance of 2 to 2.5 mm each side of centre position until the minimum value of shear strength was obtained. The rate of displacement was usually 1mm/hour and previous tests had indicated that residual strength remained essentially unchanged for slower rates of deformation. Only tests performed at values of normal effective stress $\sigma_n'=1.0$ kg/cm^2 will be reported and the residual-strength results in the figures and tables are expressed as tg ϕ_{res} where ϕ_{res} is the angle of residual shear resistance.

RESIDUAL STRENGTHS OF MIXTURES

Results of residual-strength tests on montmorillonite-quartz mixtures are plotted in Fig. 1a on the basis of dry-weight contents of total clay mineral and total massive mineral. The results indicate that the residual strength of a mixture is dependent on the relative contents of massive minerals and montmorillonite and on the residual-strength characteristics of these components, which for sodium montmorillonite is strongly dependent on salt concentration in the pore fluid.

In a mixture of clay-mineral particles, quartz particles and water, the clay mineral and water form a cohesive matrix and the quartz particles are discrete inclusions in the matrix. The strength behaviour of the mixture is dependent on the relative volumes of matrix and inclusions; for small volumes of quartz the behaviour of the mixture is controlled by the clay-mineral matrix, and increasing volumes of quartz inhibit to an increasing extent the clay-mineral particles becoming oriented parallel to the direction of shear displacement, thus causing increased shear resistance. Beyond a certain volume the massive minerals will form a continuous structure which resists applied forces, and the clay-mineral matrix only acts to fill the voids. Tests on several different massive minerals having a wide variety of grain-size distributions indicate that the porosity at residual-strength state is usually $n_{res}=0.4$ to 0.5, and therefore for mixtures in which the volume of clay mineral and water is less than 40% or 50% of the total volume, the residual strength of the mixture should be about equal to that of the massive-mineral constituents

The percentage volume of the clay-mineral and water matrix has been calculated based on the known dry-weight proportions of massive and clay minerals and on the measured water content of the mixture at residual-strength state, and these values are listed in Tables I and II. They are plotted in Fig.1b which presents a clear picture of the behaviour of mineral mixtures, and supports the idea that when the volume of massive minerals exceeds about 50% of the total volume of the mixture the residual strength of the mixture is about equal to that of the massive mineral.

Figure 4 has been prepared to compare relative residual strength of mineral mixtures, denoted by R_ϕ and expressed by the relationship:

$$R_\phi = \frac{tg\phi_{res}\text{mixture} - tg\phi_{res}\text{clay mineral}}{tg\phi_{res}\text{massive mineral} - tg\phi_{res}\text{clay mineral}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

These data indicate that the relative residual strengths of all mixtures of montmorillonite and massive minerals are similarly influenced by the relative volumes of the component clay-mineral matrix and massive minerals.

Results of tests on kaolinite and grundite mixtures are plotted in Figs. 2 and 4 and the findings are in general similar to those for the montmorillonite mixtures.

Results of tests on hydrous mica mixtures are plotted in Fig.3 and the following observations can be made.

1. Residual strength increases for increased content of massive minerals. One exception is the case of hydrous mica III, the very fine-grained material, at 30 gm NaCI/l, for which the increase of dry weight of quartz from about 10% to 35% caused a decrease of residual strength and further additions of quartz caused increases. These results were reproducible.

2. For mixtures having the same adsorbed cation, those with large salt concentrations exhibited the larger values of residual strength.

3. Potassium mixtures have larger residual strengths than sodium mixtures.

Results of tests on hydrous-mica mixtures have not been plotted in Fig.4; results of tests on mixtures containing hydrous mica I and hydrous mica II for 0gm/l would plot within the band for montmorillonite mixtures, whereas the other results would plot outside of this band.

STRENGTHS OF NATURAL AND TREATED SOILS

Table Ia contains information concerning natural soils having significant amounts of montmorillonite and mixed-layer clay minerals and which are found in nature in the form of very stiff clays or clay shales. The first nine soils (Little Belt to Pierre inclusive)

TABLE 1. PROPERTIES AND MINERAL COMPOSITIONS OF NATURAL SOILS AND MINERALS USED IN THE TEST PROGRAM.

		Plasticity		Grain Size				Massive Minerals % dry weight					Clay Minerals % dry weight						Residual State $\sigma_n' = 1.0$ kg/cm²		
Material	Salinity gm equiv. NaCl/l(1)	w_L %	w_P %	Range μ	<2μ %	Activity	Cation Exchange Capacity m. equiv./100 gm	Quartz	Feldspar	Calcite	Others	Total	Kaolin	Chlorite	Hyidrous mica, Mca, Illite	Mixed layers with Montmorillonite	Montmorillonite	Total	w_{res} %	% Volume Clay and Water	tg ϕ_{res}
A. MATERIALS CONTAINING MONTMORILLONITE																					
NATURAL SOILS																					
Little Belt, Denmark	11	121	40	< 60	58	1.4	45	2		17	5	25	10		10	5	50	75	68	91	0.16
Bearpaw, Canada	↑	117	35	< 60	50	1.6	25	20	5	1		25			15	60		75	69	91	0.11
Pierre, USA	|	145	42	< 20	56	1.8	39	15	5			20			10	←70→		80	78	94	0.10
Cucaràcha, Panama	|	59	32	<100	36?	0.7	61	10				10		←90→				90	42	93	0.11
Vajont I, Italy	|	106	35	< 75	70	1.0	55	5	5	30	10	50				←50→		50	50	79	0.18
Vajont II, Italy	|	106	40	< 75	68	1.0	79	10		7	5	20		←5→		←75→		80	48	92	0.16
Taylor I, Texas(4)	|	67	21		57	1.0		10		30		40	10		10		40	60	40(3)	81	0.15
Kincaid, Texas(4)	|	113	22		52	1.8		25	10		8	43	5		7		45	57	60(3)	85	0.09
Pierre, S. Dakota(4)	|	351	31		85	3.8		10	10			20		5	15		60	80	150(3)	95	0.05
Vajont III, Italy	Small	62	18	< 60	52	0.8	27	6		40		45		←30→		←25→		55	27	74	0.28
Sandnes II, Norway	|	71	28	< 60	80	0.5			10	5	10	25	5	15	40	10	5	75	52	90	0.25
Bearpaw, Montana(4)	|	161	29		64	2.1		20	5		20	45		15	25		15	55	70(3)	85	0.11
London-Wraysbury(5)	|	72	29		57	0.76		30				30	15	10	35		10	70	36	85	0.17
London – Walthamstow(5)	|	66	24		53	0.79		22	7	2	5	36	15		31		17	63	31	80	0.16
Strawn, Texas(4)	|	62	24		64	0.60		22	5		1	28	40		32			72	40(3)	86	0.13
Pepper, Waco, Texas	|	96	25	< 60	58	1.2	25	15	10		5	30	45		15	5	5	70	58	89	0.10
Bentonite, USA	↓	298	31	< 20	61	4.5		←25→				25	15	←<5→			60	75	90	93	0.10
PROCESSED MINERALS																					
Montmorillonite – Na(2)	0	1325	53	< 2	100	12.7	115					0					100	100	465	100	0.07
Montmorillonite – Na	30	620	45	< 2	100	5.8	115					0					100	100	219	100	0.18
B. MATERIALS CONTAINING HYDROUS MICA																					
NATURAL SOILS																					
(a) *Unweathered*																					
Manglerud I, Norway	< 2	25	18	< 60	45	0.16	11	10	30		2	40		5	50	5		60	22	75	0.30
Myrer, Norway	0.5	31	19	< 60	44	0.27	15	5	10			15		15	65	5		85	24	92	0.33
(b) *Chemically Treated*																					
Manglerud I – O_2 atmos	< 2	46	24	< 60	44	0.50	11	10	30		2	40		5	50	5		60	35	80	0.32
Manglerud I – NaCl	0	26	22	|	38	0.10	|	|	|		|	|		|	|	|		|	25	77	0.36
Manglerud I – NaCl	30	42	24	|	38	0.49	|	|	|		|	|		|	|	|		|	39	81	0.34
Manglerud I – $CaCl_2$	0	48	28	|	44	0.45	|	|	|		|	|		|	|	|		|	31	79	0.36
Manglerud I – $CaCl_2$	15	49	26	|	44	0.53	|	|	↓		↓	↓		↓	↓	↓		↓	28	78	0.31
Manglerud I – KCl	0	32	26	|	54	0.11	|	|	40			50		5	40	5		50	23	76	0.33
Manglerud I – KCl	30	50	26	|	54	0.45	↓	↓	40			50		5	40	5		50	29	78	0.38
Myrer – N_2 atmos	0.5	32	19	|	44	0.30	15	5	10			15		15	65	5		85	24	92	0.32
Myrer – O_3 atmos	0.5	45	25	|	|	0.49	|	|	|			|		|	|	|		|	26	92	0.31
Myrer – NaCl	20	43	25	|	|	0.42	|	|	|			|		|	|	|		|	26	92	0.30
Myrer – $FeCl_3$	19	47	26	|	|	0.48	↓	↓	↓			↓		↓	↓	↓		↓	26	92	0.31
Manglerud III – Na	0	26	20	|	|	0.14	11	15	15	1	5	35		15	45	5		65	32	82	0.29
Manglerud III – Na	30	47	25	↓	↓	0.50	11	15	15	1	5	35		15	45	5		65	36	83	0.30
(c) *Weathered*																					
Selnes, Norway	< 2			< 60	42		11	25	10		15	50		5	45			50	21	68	0.50
Manglerud III, Norway	|	34	21	|	44	0.30	11	15	15	1	5	35		15	45	5		65	25	80	0.56
Åsrum I, Norway	↓	37	22	|	43	0.34	9	15	15		10	40		15	45			60	25	77	0.50
Studenterlunden, Norway(5)	>10	41	21	|	38	0.54		22	17		3	42		24	34			58	25(3)	78	0.58
Labrador, Canada	< 2	32	22	|	55	0.18	13	10	20			30		15	55			70	26	82	0.50
Ottawa, Canada	|	67	31	↓	70	0.52	20	10	20		10	40		5	50	5		60	38	82	0.55
Sandnes I, Norway	↓	31	18	<200	42	0.30	13	20	10	5	5	40		20	30	10		60	24	76	0.53
PROCESSED MINERALS																					
Hydrous mica I – Na	0	47	31	< 2	100	0.16	19	5	20		5	30		10	60			70	34	85	0.31
Hydrous mica I – Na	30	81	34	|	|	0.47	|	|	|		|	|		|	|			|	41	87	0.35
Hydrous mica I – K	0	44	34	|	|	0.10	|	|	|		|	|		|	|			|	36	86	0.39
Hydrous mica I – K	30	92	42	|	|	0.50	↓	↓	↓		↓	↓		↓	↓			↓	45	87	0.48
Hydrous mica II – Na	0	51	33	|	|	0.18	38		5		5	10		5	85			90	39	96	0.29
Hydrous mica II – Na	30	99	39	|	|	0.60	|		|		|	|		|	|			|	46	96	0.43
Hydrous mica II – K	0	84	39	|	|	0.45	|		|		|	|		|	|			|	45	96	0.39
Hydrous mica II – K	30	118	46	↓	|	0.72	↓		↓		↓	↓		↓	↓			↓	47	96	0.46
Hydrous mica III – Na	0	87	46	<0.5	|	0.41	28		5		5	10		5	85			90		96	0.37
Hydrous mica III – Na	30	151	53	<0.5	↓	1.0	28		5		5	10		5	85			90	51	96	0.49
C. OTHER MATERIALS USED IN MIXTURES																					
Kaolinite	0	59	37	< 10	72	0.31	9					0	95		<5	<5		100	55	100	0.27
Grundite – Na	0	164	46	< 2	100	1.2	26					0			70	30		100	78	100	0.20
Grundite – Na	30	130	43	< 2	100	0.9	26					0			70	30		100	69	100	0.18
Quartz				2-60	0			100				100							33	0	0.69
Amorphous SiO_2	*0*	*33*	*28*	*<0.5*	*100*	*0.05*					*100*	*100*							*35*	*0*	*0.56*

1. Salinity of natural soils was determined by electrical conductivity on pore fluid.
2. Na, K and Ca homoionic materials were prepared by using solutions of NaCl, KCl and $CaCl_2$ respectively.
3. Estimated on basis of Atterberg limits.
4. Data from Townsend and Gilbert, 1973.
5. Data from Bishop *et al.*, 1971.

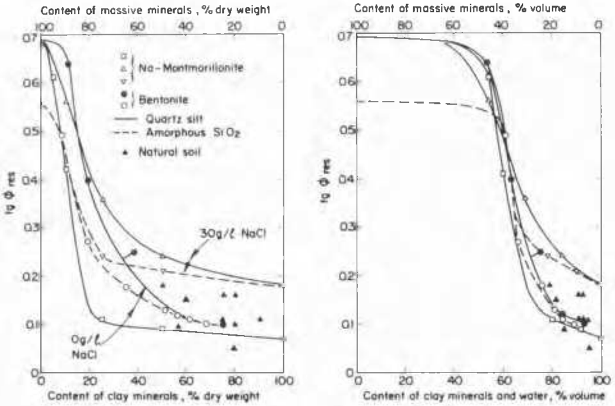

Fig. 1. Mixtures and natural soils containing montmorillonite

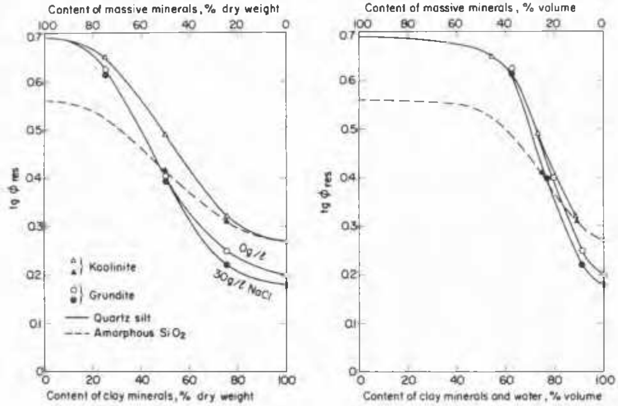

Fig. 2. Kaolinite-quartz and grundite-quartz mixtures

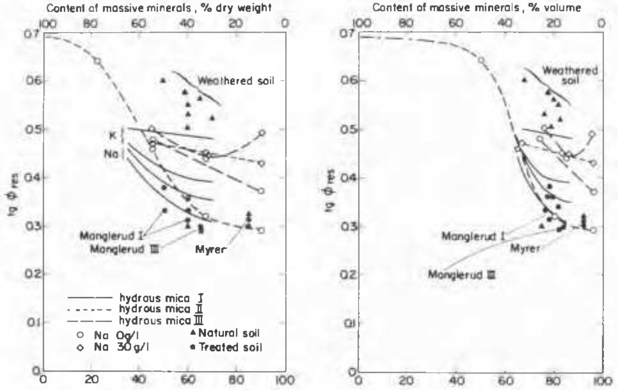

Fig. 3. Mixtures and natural soils containing hydrous mica

can be considered approximately as being mixtures of massive minerals and clay minerals which behave similarly to montmorillonite, based on their mineral composition, Atterberg limits, Activity and cation exchange capacity. Data for these soils are plotted in Fig.1a and 1b and are consistent with the results of tests on montmorillonite-quartz mixtures.

The next seven soils (Vajont III to Pepper) contain a variety of clay minerals and possess a variety of properties and index characteristics, such that it is difficult to categorize any of them as a mixture of massive minerals and a single clay mineral. Data for these seven soils have not been plotted in Fig.1,2 or 3. Residual strengths of both Vajont III and Sandnes II, which contain important quantities of montmorillonitic minerals as well as micaceous minerals, would be located on the high side of Fig.1 and on the low side of Fig.3. Bearpaw, Montana and the two London soils also contain important quantities of both montmorillonitic and micaceous minerals but their residual strengths locate comfortably in Fig.1. Strawn and Pepper shales, by virtue of their large contents of kaolin, might be expected to correspond to the relationships in Fig.2 but, in fact, they correspond to the weakest of the montmorillonite mixtures in Fig.1. No explanations for these apparent anomalies can be given.

TABLE II. RESULTS OF RESIDUAL STRENGTH TESTS ON MIXTURES.

Mixture	Salinity gm/l	Mixture % dry weight	Mineral Content % dry wt.		Residual State $\sigma_n' = 1.0$ kg/cm²		
			Total Massive	Total Clay	w_{res} %	% Volume Clay and Water	$tg\,\phi_{res}$
A. MIXTURES CONTAINING MONTMORILLONITE							
Montmorillonite – Na and Quartz	0	50/50	50	50	200	92	0.09
		25/75	25	75	96	80	0.11
		10/90	10	90	44	60	0.42
		5/95	5	95	39	54	0.61
Montmorillonite – Na and Quartz	30	50/50	50	50	72	84	0.24
		25/75	25	75	51	69	0.36
		10/90	10	90	34	54	0.56
Montmorillonite – Na and Amorphous SiO₂	30	50/50	50	50	150	90	0.21
		25/75	25	75	87	78	0.24
Bentonite and Quartz	0	75/25	44	56	61	84	0.12
		50/50	62	38	52	75	0.25
		25/75	81	19	42	63	0.40
		15/85	89	11	32	53	0.64
Bentonite and Amorphous SiO₂	0	91/9	32	68	70	89	0.10
		82/18	39	61	56	84	0.11
		68/32	49	51	68	81	0.13
		47/53	65	35	60	76	0.18
		25/75	81	19	47	66	0.27
		10/90	92	8	51	61	0.49
B. MIXTURES CONTAINING KAOLINITE AND GRUNDITE							
Kaolinite and Quartz	0	75/25	25	75	40	88	0.32
		50/50	50	50	30	73	0.49
		25/75	75	25	23	54	0.65
Kaolinite and Amorphous SiO₂	0	75/25	25	75	44	89	0.32
		50/50	50	50	31	74	0.41
Grundite – Na and Quartz	0	75/25	25	75	67	91	0.25
		50/50	50	50	49	79	0.40
		25/75	75	25	36	62	0.62
Grundite – Na and Quartz	30	75/25	25	75	63	91	0.22
		50/50	50	50	40	77	0.40
		25/75	75	25	36	62	0.62
C. MIXTURES CONTAINING HYDROUS MICA							
Hydrous mica I – Na and Quartz	0	75/25	48	52	30	74	0.35
		50/50	65	35	31	65	0.44
Hydrous mica I – Na and Quartz	30	75/25	48	52	32	75	0.38
		50/50	65	35	33	66	0.46
Hydrous mica I – K and Quartz	0	75/25	48	52	30	74	0.41
		50/50	65	35	30	65	0.47
Hydrous mica I – K and Quartz	30	75/25	48	52	41	78	0.49
		50/50	65	35	35	67	0.50
Hydrous mica II – Na	0	75/25	33	67	31	80	0.32
		50/50	55	45	22	66	0.46
Hydrous mica II – Na	30	75/25	33	67	41	83	0.45
		50/50	55	45	27	67	0.47
Hydrous mica III – Na	0	75/25	33	67	54	85	0.44
		50/50	55	45	40	74	0.48
Hydrous mica III – Na	30	75/25	33	67	52	85	0.44
		50/50	55	45	46	76	0.50

Table Ib contains information concerning natural soils in which the predominant clay mineral is hydrous mica. (The next most abundant clay mineral in these soils is chlorite which might be expected to behave similarly to hydrous mica.) Special care was taken to obtain and test two samples of unweathered Norwegian quick clay which contained very little dissolved salts and were expected to have sodium as the dominant adsorbed cation. The soils were obtained from Manglerud I and Myrer in Oslo and weathering of the samples was prevented by beginning the tests immediately after the samples were taken from the ground and performing the tests in a nitrogen atmosphere to prevent oxidation. The residual strength values are plotted in Fig.3, and agree with tests on hydrous-mica mixtures having sodium as the adsorbed cation and containing small concentrations of dissolved salts.

Samples of Manglerud and Myrer soils were chemically treated to investigate the influence of cation type and cation concentration in the pore fluid. The treatments are indicated in Table Ib but methods of treatment were different; Manglerud I samples were washed in such a way as to produce homoionic systems and in so doing any natural gels in the soils would have been removed, whereas in the case of Myrer samples strong salt solutions were added to natural soil, thus maintaining its natural

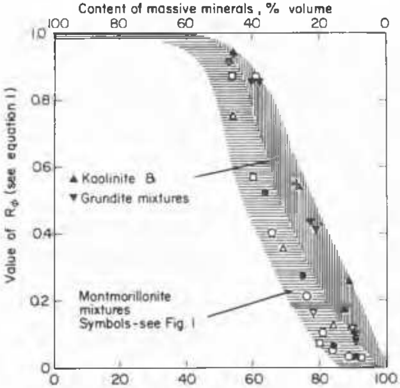

Fig. 4. Relative residual strength

content of gels but the samples would not have become homoionic. To investigate the influences of weathering, chemically untreated Myrer samples were stored for five months in nitrogen (N_2) and oxygen (O_2) atmospheres before performing the shear tests. In addition, $FeCl_3$ was added to a Myrer sample in the expectation that it would become altered and precipitate in a form of iron gel, giving the soil added strength (Moum, 1967). The obvious and most important feature of the residual strengths of these treated soils is that they differ very little from one another and from the unweathered samples in spite of the broad range of chemical treatment inflicted on the samples to produce minimum and maximum strengths. The results provide evidence in support of the minimum strengths of hydrous-mica mixtures but they indicate smaller maximum strengths than mixtures containing fine-grained hydrous mica.

The remaining seven natural soils in Table Ib were in a weathered condition when tested. The first five (Selnes to Studenterlunden inclusive) existed prior to sampling as unweathered post-glacial marine quick clays which became weathered during storage and testing in the laboratory. Ottawa had a similar geological history but it was weathered in situ. Sandnes I is an older soil which exists in situ in a heavily-overconsolidated state and was weathered in situ. The residual-strength values for these soils, without exception, plot in Fig.3 above the results of tests on the hydrous-mica mixtures and well above the results of tests on Manglerud and Myrer soils. A sample of one of the weathered soils, Manglerud III, was treated chemically by repeated mixing in NaCI solutions and washing with distilled water to produce homoionic sodium materials of small and large salt concentrations. The residual strengths of these two materials (Table Ib) were very much reduced from the values of the parent weathered soil and they plot at the lower bound of the other test results, consistent with the results of tests on Manglerud I and Myrer soils.

No explanation can be given regarding the apparent discrepancy between the residual strengths of the seven weathered natural soils and those of the other hydrous-mica materials. Possibilities exist such as the influence of natural gels in weathered natural soils, but at this time such a suggestion is only speculation.

CONCLUSIONS

1. The numerical accuracy of the mineral-composition determinations of natural soils should be considered as being only reasonably good; although great amounts of time and effort were expended on this work the interpretations were frequently based on approximate and indirect correlations. The accuracy and reproducibility of measurements of residual strength were excellent.

2. Residual strength of mineral mixtures and natural soils is dependent on their mineral composition and chemical state and on the relative volumes of clay-mineral matrix and massive minerals (Fig. 1b,2b,3b and 4).

3. Consistent comparisons were found between the results of tests on mineral mixtures and natural soils containing significant amounts of montmorillonite. Anomalies were found in the cases of Strawn and Pepper shales which exhibited small values of residual strength, similar to montmorillonitic soils, but apparently contained very little montmorillonite and large amounts of kaolin. It is not known whether or not these anomalies result from incorrect determinations of mineralogy or from unexpected properties of the kaolin.

4. Consistent results were found from tests on mixtures of hydrous mica and quartz and these results were also consistent with those for two natural quick clays. Tests on seven weathered natural soils containing significant amounts of hydrous mica gave residual strengths which were much larger than those for mixtures of hydrous mica and quartz. To find an explanation for these results unweathered natural soils were chemically treated to simulate weathering processes but these treatments had only minor influences on the residual strength, and therefore, the large residual strengths of the weathered marine clays remains unexplained.

ACKNOWLEDGEMENTS

The work was conducted at the Norwegian Geotechnical Institute and the author is indebted to the late Dr. Laurits Bjerrum for his encouragement and many helpful discussions we held concerning the work. The author gratefully acknowledges the contributions of Tor Löken and Olav Sopp who made the mineral-composition determinations of the soils, Knut Holm who performed the shear tests and Johan Moum who gave guidance on chemical treatment of the materials.

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