

EXPERIMENTAL STUDY OF THE ATTACK OF WATER ON DRY COHESIVE SOIL SYSTEMS

The mechanism of water attack on dry cohesive soil systems was studied by means of simple slaking tests on specimens prepared from five soils and a number of their homoionic variants as well as on sand-clay specimens manufactured from these soils and crushed limestone and flint sands. The observed slaking pictures and rates were analyzed with reference to such soil parameters as Atterberg limits, types and percentages of clay and organic matter, heats of wetting, and presence or absence of a granular bearing skeleton. For the natural soils, a simple exponential relationship was found between the shrinkage limits and the slaking times; however, the slaking pictures were different for expansive and nonexpansive soils and also for expansive soils possessing relatively large secondary aggregates that were protected by wetting-resistant organic films. Analysis of all the data obtained on the natural soils, their variants that gave maximum and minimum slaking times, and corresponding sand-clay systems yielded information on the mechanism and time rate of water attack on a wide range of soil systems. Analysis also suggested a possible sequence of events that cause a gradual loss of mechanical stability of mine waste dumps due to internal weathering under acid conditions and may lead to their ultimate catastrophic failure.

The interaction of soil and flowing water that leads to sheet and gully erosion may also be accompanied by or result in the usually more severe and often catastrophic phenomena of slaking and sloughing off of river banks and mud flows, especially if dry cohesive soils or similar materials such as piles of mine tailings and other mineral industrial wastes are involved. Attempts at understanding the basic mechanism of water attack on dry cohesive soil systems are germane to the purpose of this workshop. Because of the numerous physical and physicochemical factors involved, there is little hope for a truly analytic solution at the present state of theoretical development; and, if such a solution were possible, the apparatus and skill required to determine the pertinent fundamental parameters would forbid its use in most practical cases. Under these circumstances, the most promising engineering approach is the simple slaking test in combination with the commonly performed Atterberg or other simple routine test and an evaluation of the test results in accordance with present understanding of their physical meaning.

GENERAL THEORETICAL CONCEPT

It may be postulated that rate and picture of reaction depend on the relative magnitudes of the driving and resisting forces (aside from geometrical factors) whereby the sum of the driving potentials equals the total suction potential composed of the matrix and ion hydration potential (related to the heat of wetting) and the osmotic potential. Among the resistance factors are the resistance to water permeation (the inverse of permeability), the resistance of the internal soil surface to wetting (as

caused by surface films of certain types of organic matter), the bonds between primary and secondary particles, and the air in the soil pores augmented, as the case may be, by previously adsorbed air released by the advancing wetting front.

Of special importance with regard to the reaction picture is the relation between the rate of water penetration and the rate of destruction of interparticle bonds. If the rate of bond destruction equals or exceeds that of water penetration, the result will be a progressive, orderly slaking and separation of primary or secondary constituent particles. If, on the other hand, the rate of bond destruction is much smaller than that of water penetration (assuming sufficient air venting to prevent building up of gas pressure), then the system may fail only after a prolonged period of water saturation and may do so catastrophically without any apparent immediate reason.

METHOD OF TEST

Of the available methods, one originated by Russian pedologists was employed. In this method, the test specimens are formed at moisture contents slightly above the plastic limit in molds normally used for making tensile test specimens for cement mortar. After careful drying to avoid the formation of shrinkage cracks, they are coated with paraffin except for a center strip $\frac{1}{4}$ in. wide (or other adopted width) around their narrow portion. The specimens are then suspended, completely immersed in water, and the reaction picture as well as the time necessary for complete separation of the upper and lower portions is recorded. For a detailed description of specimen molding and testing see Winterkorn (2).

SOIL MATERIALS EMPLOYED

Marshall, Putnam, and Cecil subsoils and loess Pampeano topsoil and subsoil, as well as eight homoionic variations of each soil were employed. Physical, physicochemical, and chemical parameters characterizing the natural soils are given in Table 1; for those of the homoionic variants see Winterkorn (2). The organic content of the Pampeano topsoil not only is high but also possesses a marked water resistance, as shown by the low heat of wetting (H_w) of this soil.

RESULTS OF SLAKING EXPERIMENTS

Results are given for the reaction picture and the time required for the destruction of the natural soil specimens; data on the homoionic soils are introduced only insofar as they illustrate or illuminate specific points. The reaction pictures of the natural soils were as given in Table 2.

TIME REQUIRED FOR DESTRUCTION OF NATURAL SOIL SPECIMENS

Figure 1 shows plots of the logarithms of the slaking times of the natural soil specimens versus their respective LL, FME, PL, SL, and H_w values as well as the percentages of organic matter and -1μ clay contents. For easier visualization, data for the same parameters are connected by straight lines without a priori assumption of linear relationships.

The soils seem to form two distinct groups: the loess Pampeano, Marshall, and Putnam subsoils on one hand and the loess Pampeano topsoil and the Cecil subsoil on the other hand. In the first group, the slaking times decrease with increasing LL, FME, and PL values, whereas the opposite seems to hold for the Pampeano topsoil and the Cecil subsoil. In the plot of slaking time versus the -1μ clay fraction, only the Cecil soil stands alone. In view of the high content in relatively water-resistant (low heat of wetting) organic matter of the Pampeano topsoil, it may be concluded that this soil actually belongs to the first group and that its greater slaking time is due to the protection of its secondary aggregates by films of organic matter.

This is in agreement with the slaking picture. Accordingly, the Cecil soil stands alone as confirmed by the low $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio, which shows its lateritic character by the practical absence of organic constituents and by the reaction picture. The only plot that does not show a reversal is that of SL versus slaking time, although there is a discontinuity between the Putnam subsoil and the Pampeano topsoil.

For both behavioral groups, the relation between SL and slaking time can be expressed by

$$\text{Log } (t) = \frac{\text{SL} - 10}{C} + \log t_{\text{SL}=10}$$

where

t = slaking time for specimen with shrinkage limit SL,

$t_{\text{SL}=10}$ = slaking time of specimen whose shrinkage limit equals 10, and

C = difference in shrinkage limit per decade of time.

C was the same for both groups, whereas $t_{\text{SL}=10}$ was 16 min for the first and 7.5 min for the second group.

This relationship held only for the natural soils and not for their homoionic variants. However, there seems to exist a general relationship between the slaking time and the LL/SL ratio of the homoionic variants. Plots of the pertinent data permit the drawing of straight lines for the homoionic variants of the Pampeano topsoil and the Putnam, Marshall, and Pampeano subsoils. The angles of these lines with the LL/SL base line decrease with increasing clay content of the respective soils. The homoionic variants of the Cecil soil give a shotgun pattern.

The slaking times of the variants giving maximum and minimum values are given in Table 3 together with those of the natural soil specimens. Also given are slaking data obtained on mixtures of the same soils with flint and limestone sands prepared according to ASTM specifications for sand-clay. For details see Winterkorn and Choudhury (4).

DISCUSSION OF DATA OBTAINED ON NATURAL AND IONIC SOIL VARIANTS

Interestingly, the longest slaking times were found for those variants whose exchange ions tended to have a dispersing effect on the particular soils—Na-ion in all but the Cecil soil and H-ion for the Cecil soil. This is important inasmuch as the level of water resistance under otherwise equal conditions increases with increasing shrinkage limit, i.e., with increasing tendency to flocculated structure formation. To complete the paradox, we found that the flocculating Fe- and Al-ions brought about the lowest slaking times in all but the Cecil soil.

It is possible that by dispersing a portion of the secondary clay aggregates a better gradation of effective particle sizes was obtained with consequent lowering of permeability. The same result would be obtained by covering the secondary aggregates with a film of dispersed particles. Flocculating ions would have an opposite effect. It is noteworthy that the greatest absolute increase (Na-ion) and decrease (Fe-ion) in slaking times were obtained in the case of the Pampeano topsoil. Additional evidence for the proposed explanation is the great water resistance of the oven-like bird-nests that crown almost every fence and other post in the Argentine pampas. These nests are constructed by the hornero (ovenbuilder) bird of masticated Pampeano topsoil.

SOME COMMENTS ON HOMOIONIC WHOLE SOILS

Theoretically, homoionic soils appear to be ideal media for fundamental studies on the real physical and physicochemical meaning of the various consistency and other parameters normally determined and used in soil engineering. Unfortunately, homoionic variants are not so well defined, physically and chemically, as would be desirable and as is often assumed.

Table 1. Physical properties of natural soils.

Property	Loess Pampeano Subsoil	Marshall Subsoil	Putnam Subsoil	Loess Pampeano Topsoil	Cecil Subsoil
LL	67	52	35	40	75
PL	31	24	18	27	38
PI	36	28	17	13	37
SL	12.8	13.7	15	21	32
FME	44	37	23	33	41
H _w	5.5	2.8	2.8	0.69	2.02
Water intake	0.96	0.69	0.68	0.69	0.88
Percentage <No. 40					
0.05-0.005 mm	39	55	55	53	9
<0.005 mm	50	37	33	27	76
<0.001 mm	30	22	12	10	62
SiO ₂ /R ₂ O ₃	3.6	3.2	3.2	3.1	1.3
Organic matter, percent	1.95	2.2	<1	4.5	0
Slaking time, min	25	30	38	49	328

Note: H_w is measured in cal/gram of dry soil; water intake in cc H₂O/gram of dry soil.

Table 2. Reaction picture of soils tested.

Soil	Reaction Picture
Loess Pampeano subsoil	Rapid corrosion and dispersion into very small particles; water muddy
Marshall subsoil	Swelling of the specimen and disintegration into small secondary and primary particles
Putnam subsoil	Rapid corrosion and dispersion into small secondary particles; some swelling of specimen
Loess Pampeano topsoil	Disintegration into soil aggregates of intermediate size; some swelling
Cecil subsoil	Specimen keeps integrity until clean fracture separation of lower from upper portions

Figure 1. Slaking times of natural soil specimens versus various parameters.

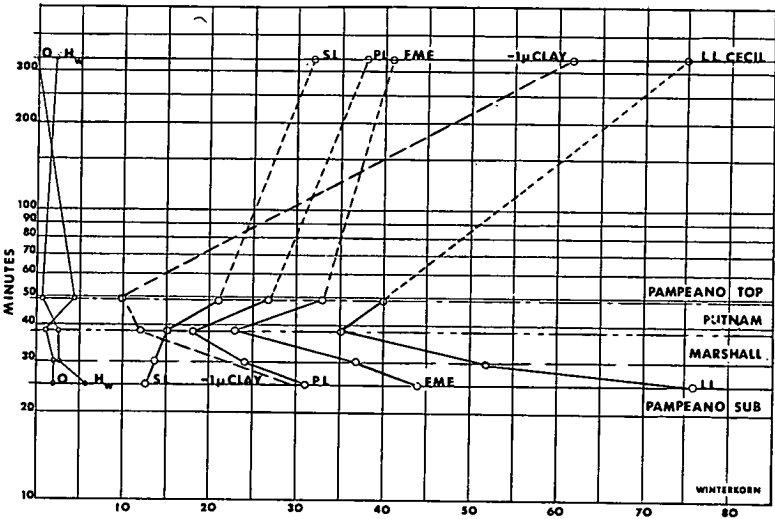


Table 3. Slaking times of natural soils and their ionic variants.

Soil	Time (min)			Range of t _{max} to t _{min}
	t _{nat}	t _{max}	t _{min}	
Pampeano subsoil	25	28 (Na)	8 (Al)	0.80
Plus limestone sand	13	179 (Na)	7 (Al)	13.2
Plus flint sand	6	55 (Na)	4 (Al)	8.5
Marshall subsoil	30	159 (Na)	17 (Fe)	4.7
Plus limestone sand	17	355 (Na)	10 (H)	20.3
Plus flint sand	6	360 (Na)	4 (K, Al, Fe, H)	59.0
Putnam subsoil	38	138 (Na)	20 (Fe)	3.1
Plus limestone sand	17	255 (Na)	<5 (K, Al)	14.7
Plus flint sand	13	240 (Na)	6 (H)	18.0
Pampeano topsoil	44	266 (Na)	6 (Fe)	5.9
Plus limestone sand	15	92 (Na)	7 (Fe)	5.7
Plus flint sand	10	39 (Na)	3 (Fe)	3.6
Cecil subsoil	328	360 (H)	188 (Mg)	0.5
Plus limestone sand	114	209 (Mg)	59 (Na)	1.3
Plus flint sand	54	110 (Na)	39 (H)	1.3

In the preparation of homoionic variants either by percolation with aqueous solutions of salts of the desired exchange ion and subsequent washing with distilled water (and often water-alcohol mixtures) or by making first H-soils by the use of acid solutions or of electrodialysis with subsequent neutralization by hydroxides of the chosen cations, large amounts of saline or acid solutions or both and of distilled water or water-alcohol mixtures are employed. Their use deprives the original soils of soluble inorganic or organic constituents or both that may have a marked or even critical effect on soil behavior. Also, it is well known that the effect of different exchange ions on the normally determined physical soil parameters is essentially an indirect one through modification of the state of aggregation of the primary soil constituents, i.e., the soil structure. The latter is also affected by the entire past history of a specific soil sample, which may differ for the different ionic variants. These facts must be taken into account in the evaluation of data obtained on homoionic soil materials.

DISCUSSION OF DATA OBTAINED ON SAND-CLAY SPECIMENS

The purpose of this phase of the investigation was to obtain some idea about the interaction of cohesive silt-clay soils with bearing skeleton forming larger grains, the possibility and degree of bond formation, and the influence of volumetric relationships on the slaking phenomenon. To reduce the influence of grain shape as much as possible while providing a variable in mineral type required the use of crushed flint and limestone sands of the same gradation.

The data given in Table 3 translate into the following picture. If we assume in first approximation that the rate of advance of the wetting front into the specimens made of the natural soils and of the soil-sand mixtures was the same, then the water resistance of the effective interparticle bonds was reduced by the limestone sand admixture to a fraction of from 0.57 to 0.34 and by the flint sand admixture to one of 0.34 to 0.16 of the value for the natural soil. The greatest reduction was obtained by the combination of flint sand with natural Cecil soil.

Considering the cationic soil variants that by themselves gave longest slaking times (Na-ion for all but the Cecil soil), we see that admixtures of both types of sand markedly decreased the slaking time of the Cecil soil and even more that of the Pampeano topsoil. It should be remembered that the natural Cecil soil and its ionic variants had the longest slaking times and greatest water resistance of interparticle bonds of all the soils tested, whereas the Pampeano topsoil held second place with respect to slaking time though its slaking resistance was governed by a different mechanism.

In the case of the Na-variants of the Pampeano, Marshall, and Putnam subsoils, provision of an interconnected granular bearing skeleton by the sand admixtures increased the slaking times a considerable extent. However, a great numerical difference between the effects of the two types of sand was evident only in the case of the Pampeano subsoil, the limestone sand being more than three times as effective as the flint sand.

In the systems giving longest slaking times, differentiation between several behavior groups may be made:

1. Among the Cecil soil variants, the natural soil as well as its cationic variants develop characteristic interparticle bonds of great water resistance. These bonds are disturbed and weakened by the admixture of either type of sand; the provision of a granular bearing skeleton does not appear to have any beneficial effect on the slaking behavior of these soils.

2. The protective mechanism possessed by the Pampeano topsoil (films of wetting-resistant organic matter over secondary particle aggregates) is weakened or even destroyed by the sand admixtures (more by the flint than by the limestone sand). As in the case of the Cecil soils, there seems to be no special advantage to the presence of the granular skeleton.

3. In the case of the Marshall and Putnam subsoils, the very presence of the granular skeleton appears to be the dominant factor regardless of the type of sand mineral involved. Obviously, the intergranular spaces not occupied by the skeleton are sufficient to accommodate the swelling of the clay particles caused by the advancing water front. This swelling decreases the permeability of the soil system and increases the slaking times.

4. In the case of the Pampeano subsoil, there appears to be a combination of bond-forming tendency with the limestone sand and swelling accommodation in the intergranular spaces of the bearing skeleton. The importance of such swell accommodation for soil stabilization has been discussed by Winterkorn and Choudhury (4), who also developed pertinent equations for the advance of the water front into specimens showing different types of slaking.

DISCUSSION OF SYSTEMS EXHIBITING MINIMUM SLAKING TIMES

With perhaps one exception (Fe-Pampeano topsoil plus limestone sand), all ionic soil variants that gave minimum slaking times gave even shorter ones in combination with the sands; those with limestone sand had somewhat better slaking resistance than those with flint sand. With the exception of the Cecil soil systems, the general slaking behavior of these soil and soil-sand systems resembled more that of rapidly corroding silts than that of normal cohesive soils. This seems to be paradoxical inasmuch as the Al-, Fe-, and H-cations that pushed all but the Cecil soil into silty behavior might have been expected to make the soils whose clays possessed a $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of more than 3 behave more like the Cecil soil. In addition to other important factors, there exists a great difference in the pH environment in which Fe and Al soil variants are produced in the laboratory and that of normal genesis of clays of low $\text{SiO}_2/\text{R}_2\text{O}_3$ ratios. Whatever the detailed explanation is, the fact is that, by treatment with acid Fe- and Al-salt solution followed by one or more drying and wetting cycles, cohesive clay soils may shift toward silty behavior. This may be very important with regard to the stability of certain soil structures in which such changes occur. Let us consider the following example.

Coal mine overburden and tailings of shaly character are dumped into piles of sufficiently loose packing to provide relatively easy access to air and precipitation water. This looseness is attested to by Schmidtalbers (1), who observed and recorded that during dumping the material in such piles behaved as macromeritic liquids (5). In their new exposure to weathering conditions (permeating water and air, temperature, and wetting-drying cycles), the mechanically produced secondary shale particles gradually return to their original clay character. At the same time the always-present pyrites and other sulfides produce acid Fe- and Al-salt solutions that react with these clay materials and produce the corresponding cationic variants at the surface of the original shale particles. In the end, these systems have lost the granular character of the original comminuted shale and have acquired the characteristics of soft aggregates covered by a layer of silt-like material. At this stage, soaking of the pile by prolonged precipitation may result in a condition similar to that caused in an earth dam by rapid draw-down of an adjoining water reservoir. The final event may be a catastrophic failure of the waste dump.

CONCLUSIONS

1. Simple slaking tests in combination with the common Atterberg limit tests are valuable tools for the study of the attack of water on dry cohesive soil systems.

2. Of special significance with regard to the strength of inter-particle bonds in natural cohesive soils not possessing a granular bearing skeleton and the rate of destruction of these bonds by an advancing wetting front is the position of the shrinkage limit. The higher this limit is, the longer is the time required for slaking or other type of specimen failure.

3. At comparable clay contents, shrinkage limits and water resistance increase with decreasing $\text{SiO}_2/\text{R}_2\text{O}_3$ ratio of the clay fraction.

4. Relatively high shrinkage limits and corresponding slaking times may also be obtained in natural soils whose secondary aggregates are protected by a film of wetting-resistant organic matter.

5. The slaking times of homoionic variants of natural soils show certain vagaries that are probably due to loss of some mineral or organic constituents by true or colloidal solution in the large amounts of liquids employed in their preparation. An additional factor is the different treatment history of the ionic variants, which leaves its imprint on their secondary structure.

6. Exchange ions that have a dispersive tendency generally increase the slaking times of whole soils, whereas flocculating ions tend to decrease them.

7. Sand-clay systems prepared from the natural and homoionic soil variants may exhibit longer or shorter slaking times than the corresponding soils. Decrease occurs when strong original interparticle bonds are replaced by weaker ones with the alien sand admixture without beneficial effect due to the presence of the granular bearing skeleton. Increases in slaking times occur when the intergranular space can accommodate the swelling of the clay fraction with a resulting decrease of the permeability of the system. This essentially geometric or volumetric effect may be modified by bond formation between the clay particles and the surfaces of the sand grains.

Other more specific conclusions were presented in the text of this paper.

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